Lead Ions in the LHC

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Outline of talk

- Introduction – the LHC and its experiments
- LHC in the lineage of heavy ion facilities
- Lead ion injector chain
- Design parameters of the LHC as a lead ion collider
- Accelerator physics issues limiting the performance
- Schedule
  - So people will stop asking me …

Introduction

- LHC designed mainly as a proton-proton collider

  But was not not called “LPC” for nothing …

- Will also operate as heavy ion collider for something like 1 month/year
- ALICE experiment dedicated to ions, CMS and ATLAS also interested

  The acceptable luminosity for heavy-ion physics is limited by the capabilities of the experiments.

Ions for LHC (I-LHC) home page - Microsoft Internet Explorer provided by CERN

File Edit View Favorites Tools Help

Links Google Mathematical Functions Oxford Reference

Address http://carli.home.cern.ch/carli/ILHC_website/

Ions for LHC (I-LHC) Project

Homepage	Mandate	LHC ion injector chain	I-LHC steering group
Minutes of meetings	Reports		Links

Aim of the I-LHC Project : The aim of the I-LHC project is to consider all aspects to be taken into account and, all hardware additions necessary, in order to allow heavy ion operation of the LHC, in addition to proton operation. The projects deals :

- with LHC related aspects and issues limiting the performance during ion operation and,
- the complete LHC ion injector chain from the source to the SPS and including accumulation in LEIR as central part.

I-LHC Project Leader : Karlheinz Schindl

Aim of the LEIR Project : LEIR is a central part of the ion injector chain for LHC. The low intensity ion beam coming from Linac 3 will be accumulated and cooled with strong electron cooling, in order to obtain dense ion bunch useful for LHC ion operation. To this end, the existing LEAR machine will be reconstructed and modified, based on

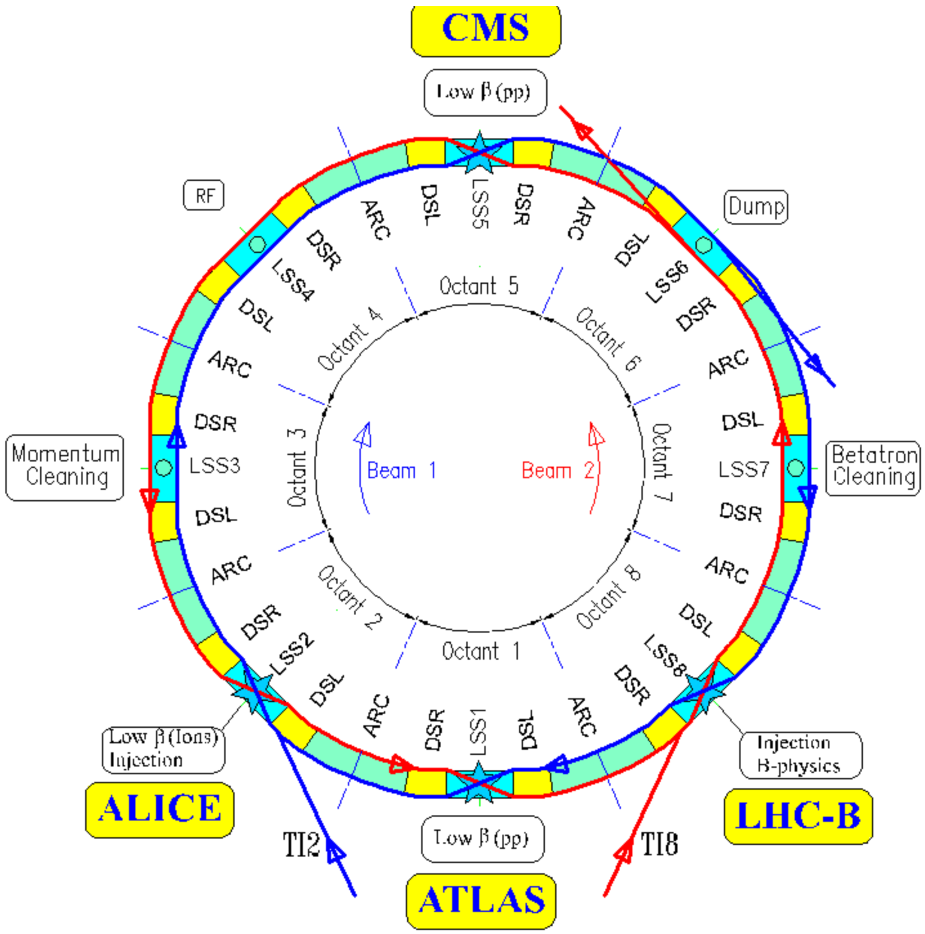
Local intranet

Lead ions in LHC main ring: credits

- Karlheinz Schindl
  overall I-LHC project leader
- John Jowett
  LHC main ring
- Hans Braun
  collimation
- Moira Gresham (Reed College, Portland)
  ECPP, software
- Bernard Jeanneret
  nuclear effects, aperture
- Edgar Mahner
  Vacuum: desorption studies
- Igor Pshenichnov (INR, Moscow)
  nuclear cross sections
- Elena Shaposhnikova
  longitudinal dynamics
- + many others in LHC project
  Optics, instrumentation, etc.
  - Pre-2003: Daniel Brandt, …

The LHC

Collisions with ions



- Consider $^{208}Pb^{82+}$-$^{208}Pb^{82+}$ collisions for now

  CM energy 1.15 PeV with nominal dipole field.

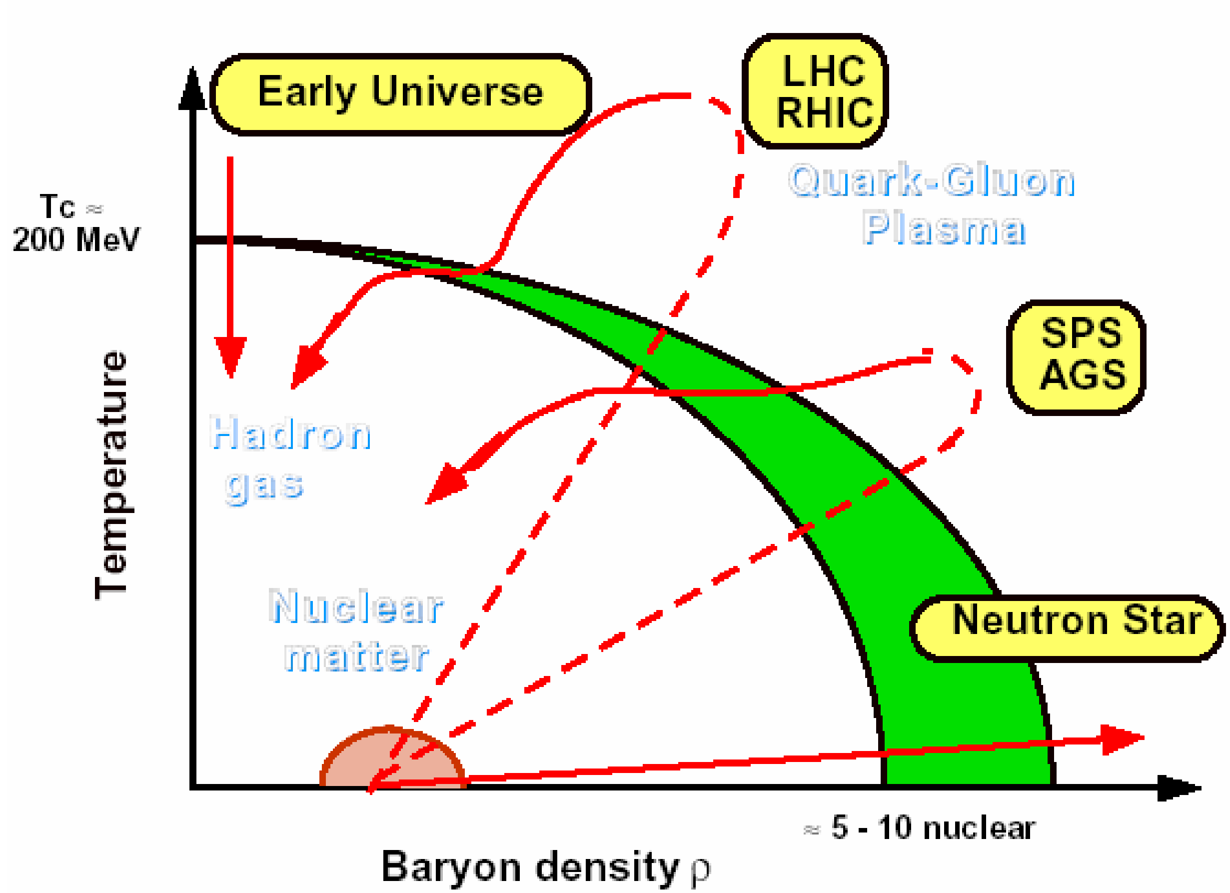
  Beam energy 2.76 TeV/u

  - p-Pb, p-A etc. later
- ALICE detector specialises in heavy ion physics
- CMS and ATLAS are also interested in ions

  At nominal luminosity/bunch, initial lifetime is short with 3 active experiments.

  - Run with 1 or 2 experiments or adapt luminosity during fill.

Hadronic matter



Phase diagram of hadronic matter showing phase transition from hadron gas to quark-gluon plasma. Predictions of QCD.

Source: J. Schukraft

Heavy Ion Physics Parameters

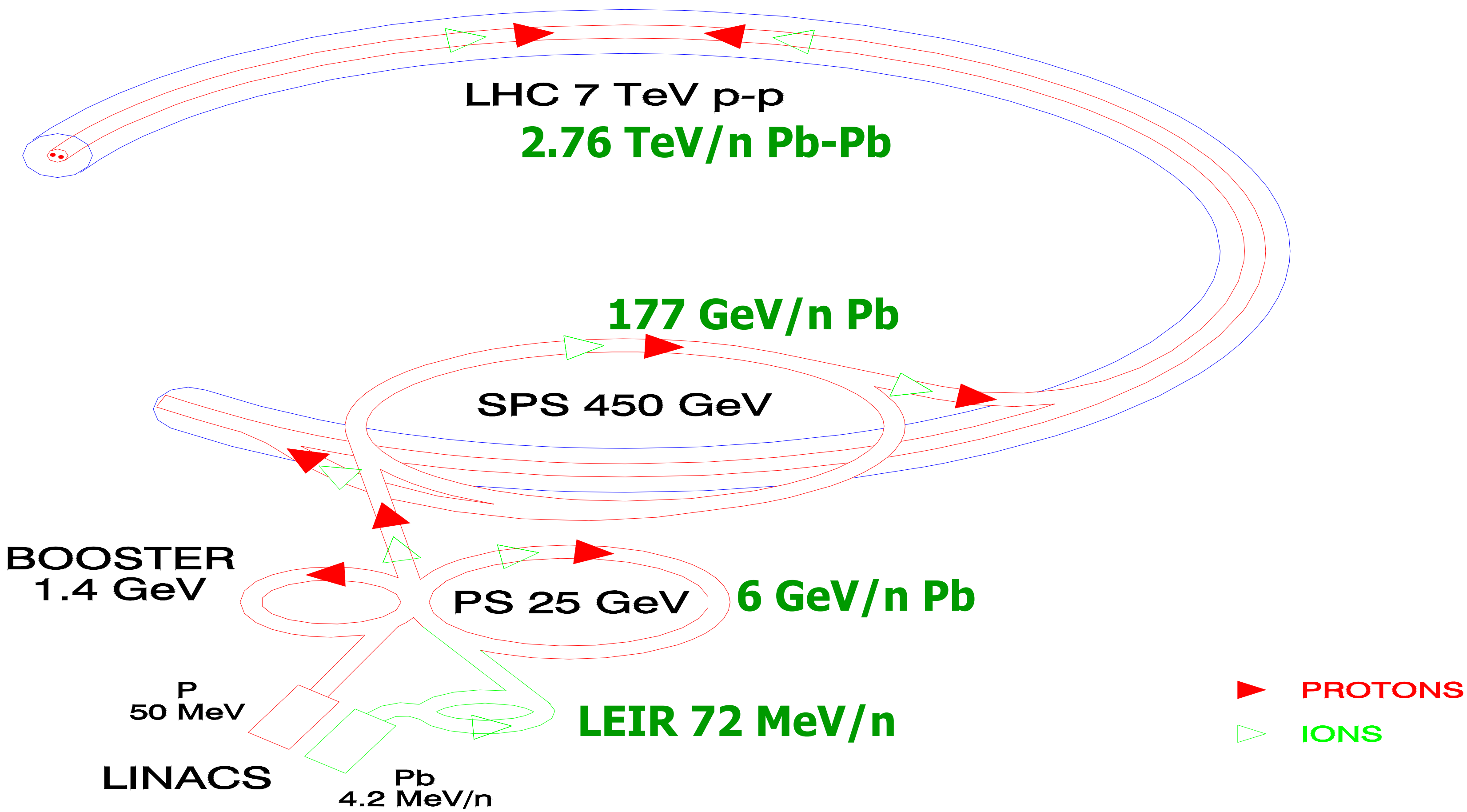
		SPS	RHIC	LHC	
CM energy / nucleon	$\sqrt{s}\,/\,u\,/\,[\mathrm{GeV}]$	17	200	5500	$\times 28$
Charged multiplicity	$\frac{dN_{ch}}{dy}$	400	800	> 3000	challenge
Energy density	$\epsilon\,/\,[\mathrm{GeV}\,/\,\mathrm{fm}^3]$	3	5	$15-60$	denser
Freeze – out volume	$V_f\,/\,\mathrm{fm}^3$	$\approx 10^3$	$\approx 10^4$	$\approx 10^5$	larger
QGP lifetime	$\tau_{\mathrm{QGP}}\,/\,[\mathrm{fm}\,/\,c]$	$\leqslant 1$	$1.5-4$	> 10	longer
Thermalization time	$\tau_0\,/\,[\mathrm{fm}\,/\,c]$	$\geqslant 1$	≈ 0.2	$\leqslant 0.1$	faster
	$\tau_{\mathrm{QGP}}\,/\,\tau_0$	1	6	$\geqslant 30$	

With increasing energy, more partons are available, interact more effectively. Thermalized high-T phase established more quickly and lasts longer.

Source: J. Schukraft, Y. Schutz

The LHC Injector Chain - Schematic

Not to scale



Injector chain slides from K. Schindl

LHC Pb Injector Chain:
Key Parameters for luminosity 10^{27} $cm^{-2}\ s^{-1}$

	ECR Source →	Linac 3 $\xrightarrow{4}$	LEIR →	PS $\xrightarrow{13,12,8}$	SPS $\xrightarrow{12}$	LHC
Output energy	**2.5 KeV/n**	**4.2 MeV/n**	**72.2 MeV/n**	**5.9 GeV/n**	**177 GeV/n**	**2.76 TeV/n**
^{208}Pb charge state	**27+**	**27+ → 54+**	**54+**	**54+ → 82+**	**82+**	**82+**
Output Bρ [Tm]		2.28 → 1.14	4.80	86.7 → 57.1	1500	23350
bunches/ring			2 (1/8 of PS)	4 (or 4x2)[4]	52,48,32	592
ions/pulse	$9\ 10^9$	$1.15\ 10^9$ [1])	$9\ 10^8$	$4.8\ 10^8$	$\leq 4.7\ 10^9$	$4.1\ 10^{10}$
ions/LHC bunch	**$9\ 10^9$**	**$1.15\ 10^9$**	**$2.25\ 10^8$**	**$1.2\ 10^8$**	**$9\ 10^7$**	**$7\ 10^7$**
bunch spacing [ns]				100 (or 95/5)[4]	100	100
ε*(nor. rms) [μm][2]	**~0.10**	**0.25**	**0.7**	**1.0**	**1.2**	**1.5**
Repetition time [s]	0.2-0.4	0.2-0.4	3.6	3.6	~50	**~10'fill/ring**
ε_{long} per LHC bunch[3]			0.025 eVs/n	0.05	0.4	1 eVs/n
total bunch length [ns]			200	3.9	1.65	1

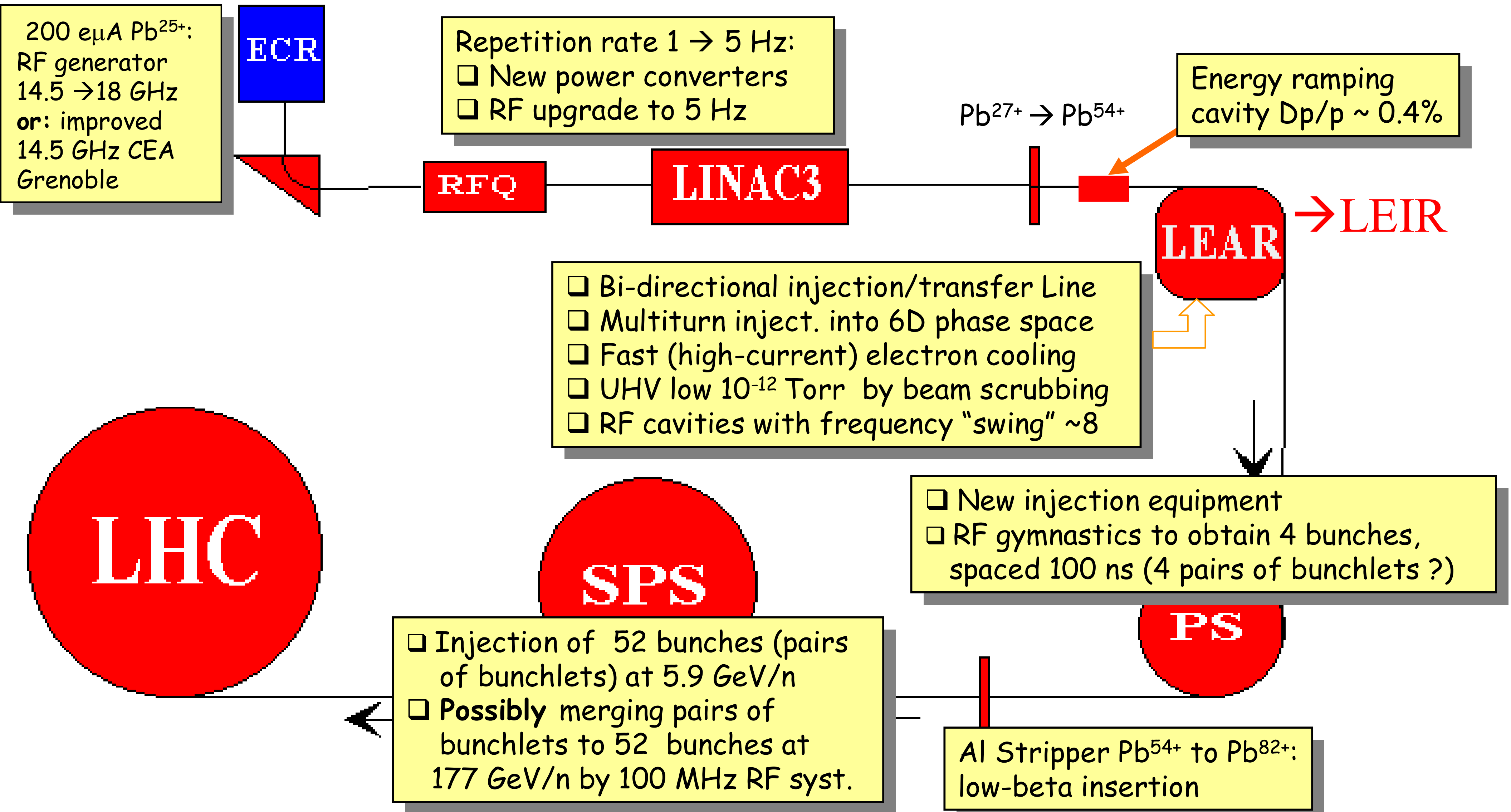
[1] 50 eμA_e x 200 μs Linac3 output after stripping

[2] Same physical emittance as protons, with the same tight emittance budget

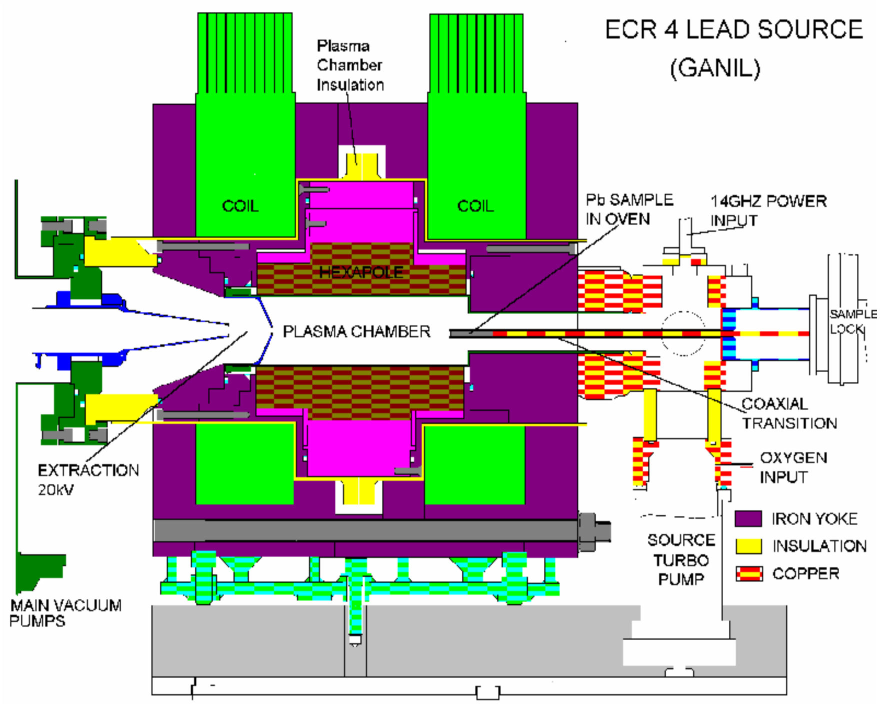
[3] For $^{208}Pb^{82+}$, 1 eVs/n ~ 2.5 eVs/charge

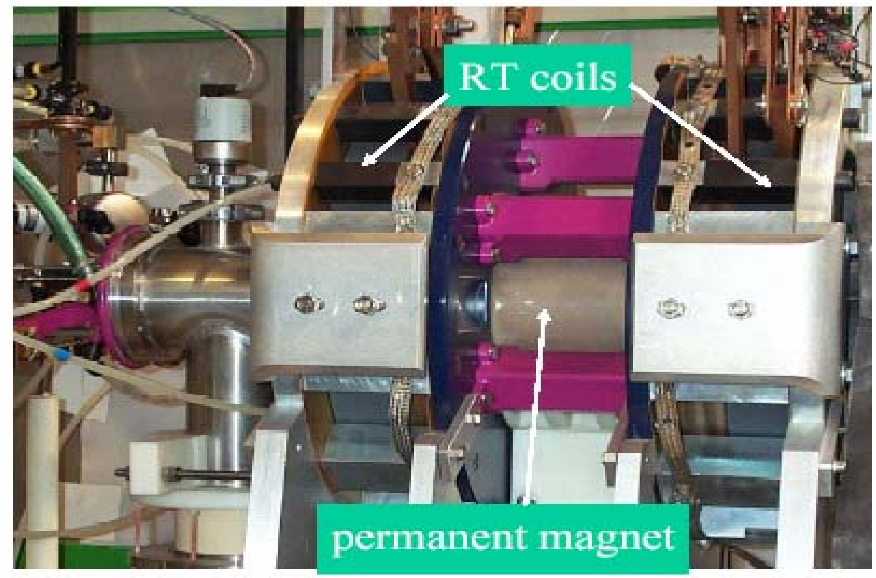
[4] If bunchlets are used in the SPS

Pb Ions for LHC: Hardware Upgrades



Heavy Ion (Lead) Linac3 Source





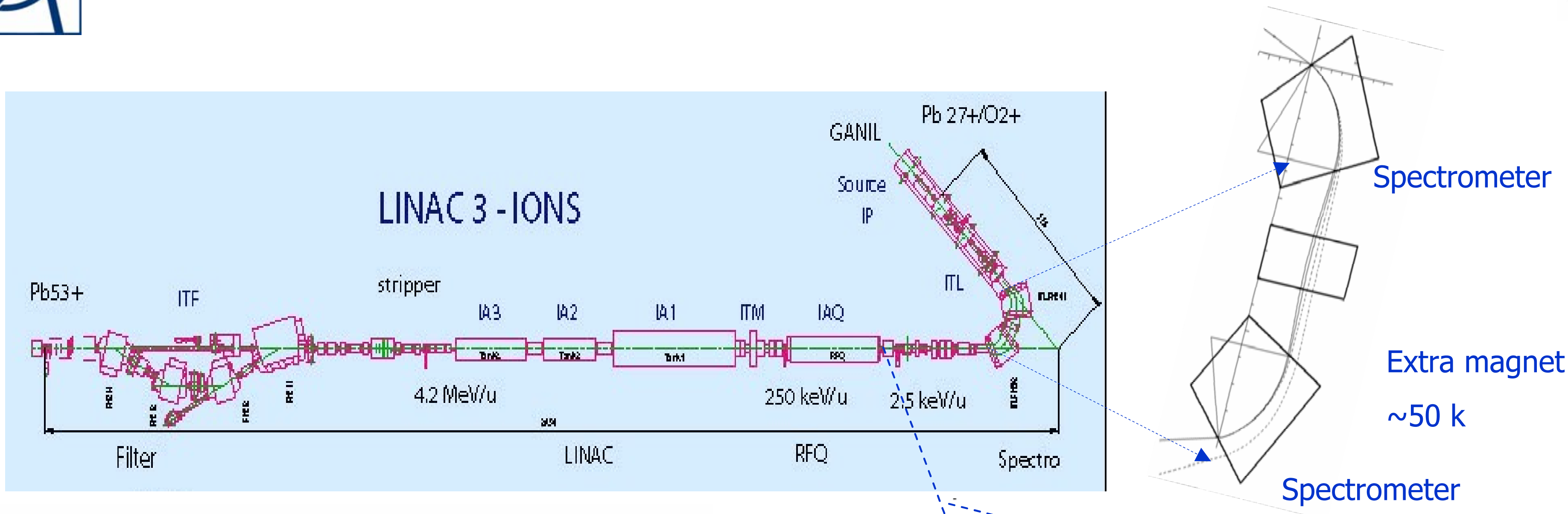
GTS (Grenoble Test Source) from CEA

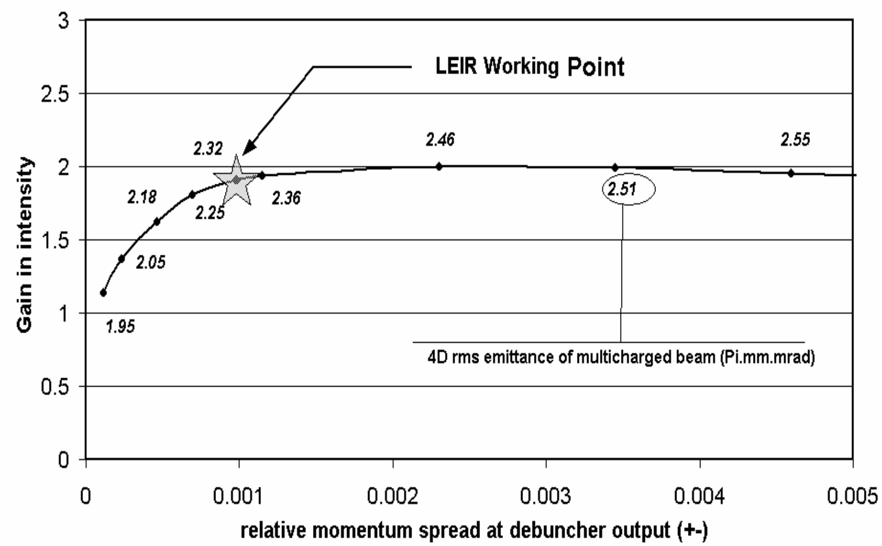
Present ECR (Electron Cyclotron Resonance Source) delivers ~ 120 eμA x 200 μs Pb^{27+}. To get near the nominal 200 eμA, upgrading from 14.5 to 18 GHz microwave frequency may be envisaged

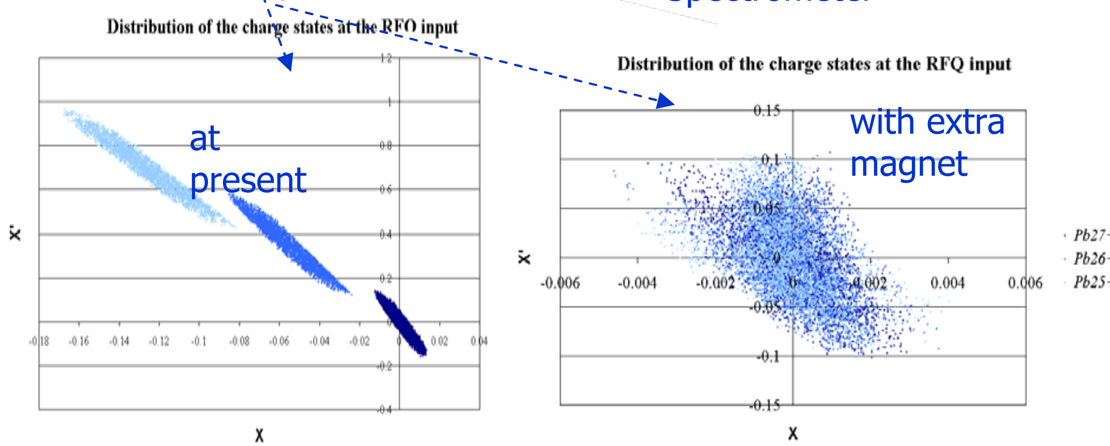
ECR source with super-performance: >200 eμA with 14.5 GHz expected (proven with Bi)
Purchase of a GTS source being negotiated

LEIR Running-in + Early Scheme feasible with present source, albeit without margin

Lead Charge States 25+,26+,27+ in Linac3







Horizontal Phase plane at RFQ entry

Extra magnet makes spectrometer dispersion-free

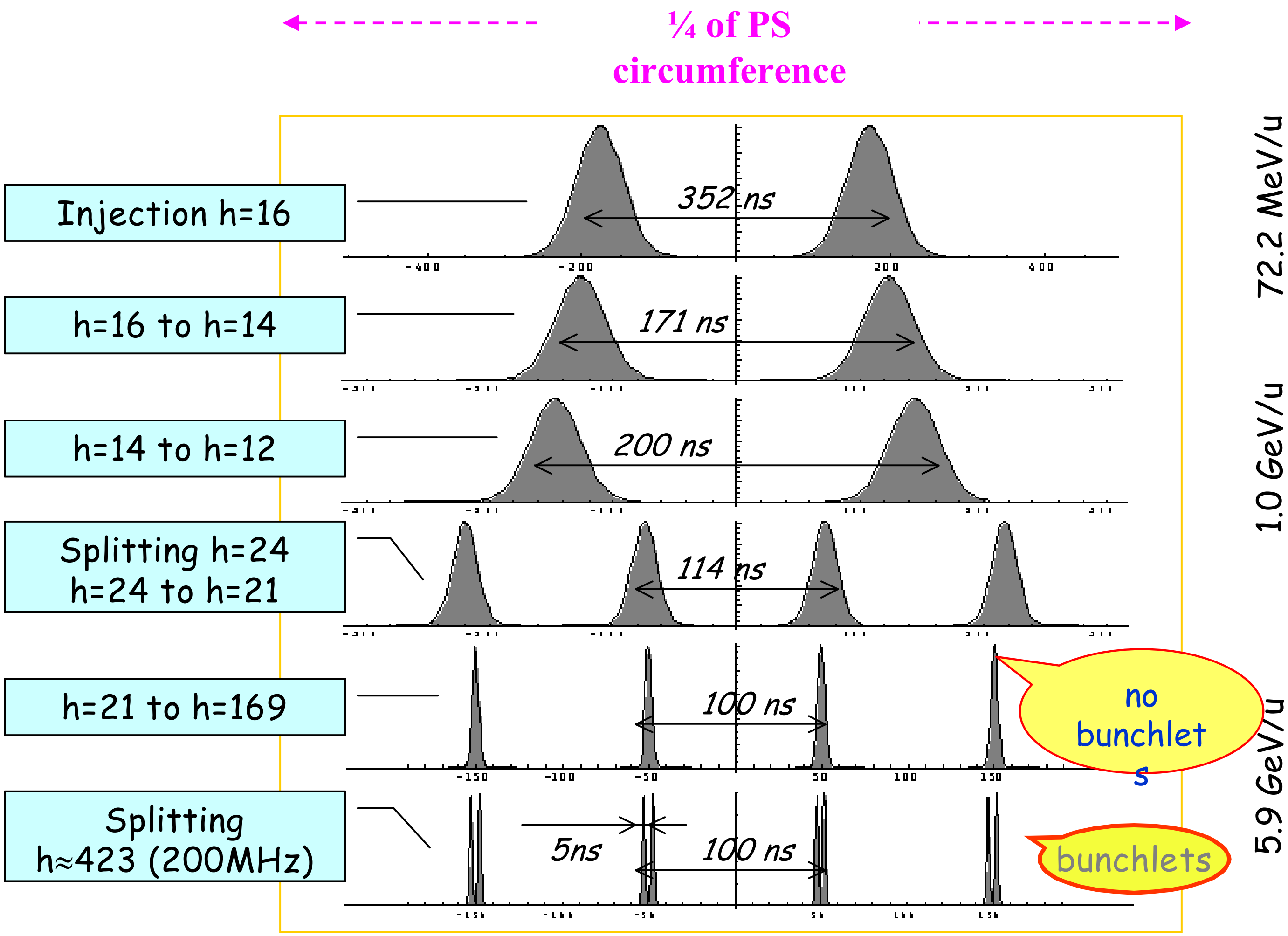
Results partially verified experimentally:

Intensity gain factor >1.5 appears realistic

A. Lombardi, V. Coco, R. Scrivens, E. Sargsyan

RF Gymnastics in the PS for Pb ions

Skip LEIR



M. Chanel, S. Hancock, M. Martini

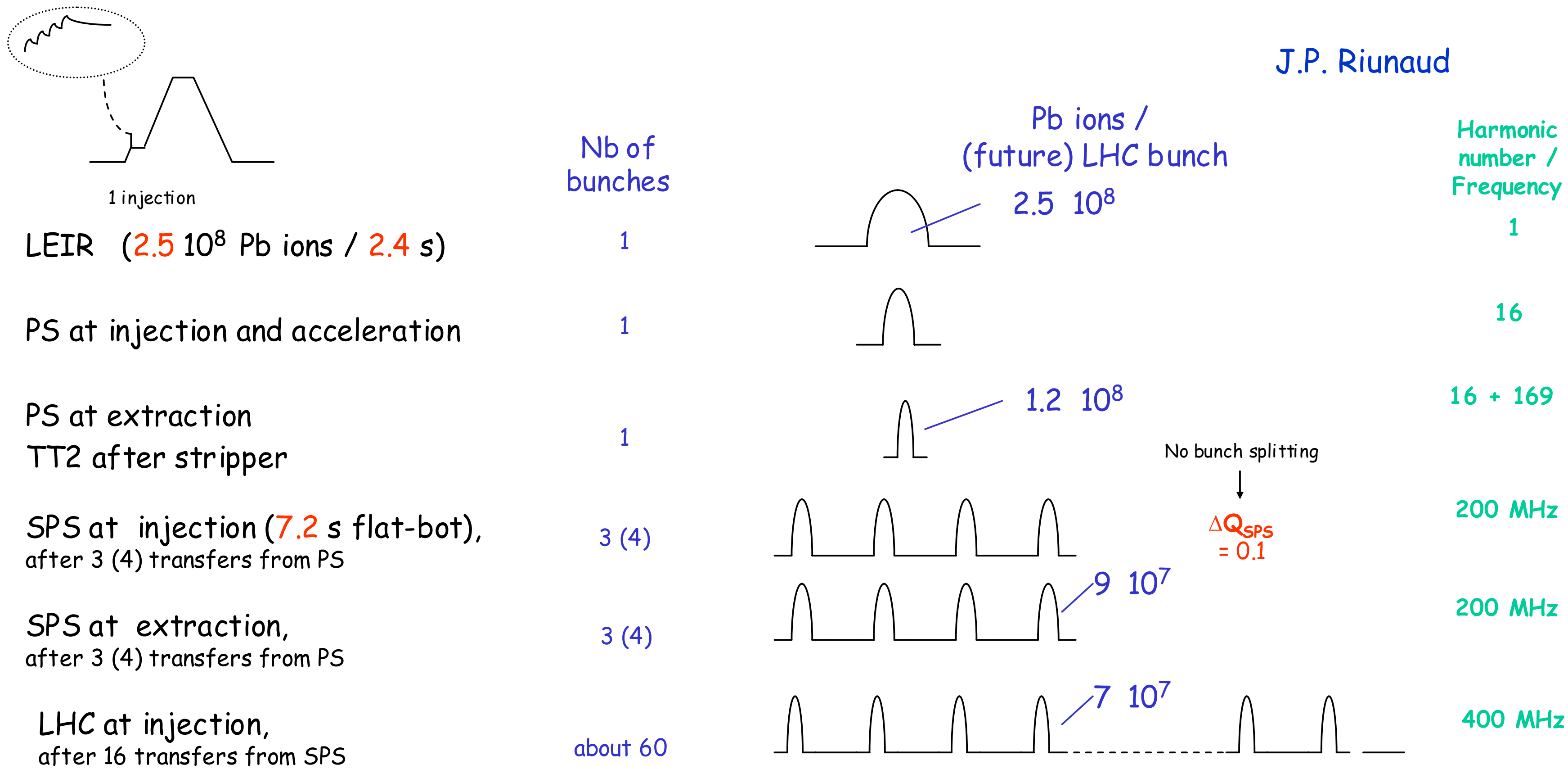
Chamonix XII - Session 2 Summary – J.-P. Riunaud 13

SPS

- Bunchlets – Yes or No?
  - Injection plateau lasting 43.2 s at 57.1 Tm, accumulating up to 13 PS batches of 4 bunches (4 pairs of bunchlets) each. Very little transverse blow-up/losses allowed
  - Pb ions suffer from incoherent space charge detuning and Intra-Beam Scattering (IBS)
  - Halving the number of ions/bunch (= making bunchlet pairs) halves these effects as well.
  - Bunchlet pairs can be recombined by a 100 RF system before extraction to the LHC
  - Space charge detuning ΔQ (about the same in either plane) for nominal Pb ion bunches:
    - 0.082 calculated
    - $p\bar{p}$ experience: SPS can stand not more than $\Delta Q = 0.07$
    - Recent measurements (with p): DQ up to 0.18 acceptable on the injection plateau
  - IBS growth times (nominal bunches): ~300 s which is acceptable
  - ΔQ and IBS the same for Nominal and Early schemes (bunch properties identical)
- No bunchlets in the early scheme ("calculated risk")
- No installation of 100 MHz RF systems now (intended to limit their impact on p beams)

Early Lead Operation Scheme

- Lower L=5 10^{25} $cm^{-2}s^{-1}$ (factor 20) by fewer bunches (1/10) and β^*=1
- Keep nominal bunch population (7 10^7 ions/bunch) to study limitations
- L useful for physics (early discoveries)
- much easier for injectors (Linac3, LEIR, PS), shorter LHC filling time (4′/ring)
- improved Luminosity lifetime because of larger β^*



Parameters for Lead Ions in LHC

- Revision/verification of all parameters
  - Started at Chamonix Workshop 2003
  - Summarised in forthcoming LHC Design Report Vol I, Chapter 21 (already on Web site)
- Recent changes:
  - Optics update, crossing scheme for ALICE
  - Introduction of "Early Ion Scheme"
  - Performance limit from ECPP (later …)
  - Complete revision of lifetimes, IBS, etc.
  - First studies of collimation of lead ions
  - No 200 MHz RF system for capture at injection now

Nominal scheme parameters

		Injection	Collision
Beam parameters			
Lead ion energy	[GeV]	36900	574000
Lead ion energy/nucleon	[GeV]	177.4	2759.
Relativistic “gamma” factor		190.5	2963.5
Number of ions per bunch		$7. \times 10^7$	
Number of bunches		592	
Transverse normalized emittance	[μm]	1.4[a]	1.5
Peak RF voltage (400 MHz system)	[MV]	8	16
Synchrotron frequency	[Hz]	63.7	23.0
RF bucket half-height		1.04×10^{-3}	3.56×10^{-4}
Longitudinal emittance (4σ)	[eV s/charge]	0.7	2.5[b]
RF bucket filling factor		0.472	0.316
RMS bunch length[c]	[cm]	9.97	7.94
Circulating beam current	[mA]	6.12	
Stored energy per beam	[MJ]	0.245	3.81
Twiss function $\beta_x = \beta_y = \beta^*$ at IP2	[m]	10.0	0.5
RMS beam size at IP2	μm	280.6	15.9
Geometric luminosity reduction factor F[d]		-	1
Peak luminosity at IP2	[$\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	-	$1. \times 10^{27}$

Nominal scheme, lifetime parameters

		Injection	Collision
Interaction data			
Total cross section	[mb]	-	514000
Beam current lifetime (due to beam-beam)[a]	[h]	-	11.2
Intra Beam Scattering			
RMS beam size in arc	[mm]	1.19	0.3
RMS energy spread $\delta E/E_0$	$[10^{-4}]$	3.9	1.10
RMS bunch length	[cm]	9.97	7.94
Longitudinal emittance growth time	[hour]	3	7.7
Horizontal emittance growth time[b]	[hour]	6.5	13
Synchrotron Radiation			
Power loss per ion	[W]	3.5×10^{-14}	2.0×10^{-9}
Power loss per metre in main bends	$[\mathrm{Wm}^{-1}]$	8×10^{-8}	0.005
Synchrotron radiation power per ring	[W]	1.4×10^{-3}	83.9
Energy loss per ion per turn	[eV]	19.2	1.12×10^{6}
Critical photon energy	[eV]	7.3×10^{-4}	2.77
Longitudinal emittance damping time	[hour]	23749	6.3
Transverse emittance damping time	[hour]	47498	12.6
Variation of longitudinal damping partition number[c]		230	230
Initial beam and luminosity lifetimes			
Beam current lifetime (due to residual gas scattering)[d]	[hour]	?	?
Beam current lifetime (beam-beam, residual gas)	[hour]	-	< 11.2
Luminosity lifetime[e]	[hour]	-	< 5.6

Early scheme Parameters

		Injection	Collision
Beam parameters			
Number of bunches		62	
Circulating beam current	[mA]	0.641	
Stored energy per beam	[MJ]	0.0248	0.386
Twiss function $\beta_x = \beta_y = \beta^*$ at IP2	[m]	10.0	1.0
RMS beam size at IP2 [e]	[μm]	280.6	22.5
Peak luminosity at IP2	[cm^{-2}sec^{-1}]	-	5.4×10^{25}
Interaction data			
Beam current lifetime (due to beam-beam)[a]	[h]	-	21.8
Synchrotron Radiation			
Power loss per metre in main bends	[Wm^{-1}]	8.5×10^{-9}	5.0×10^{-4}
Synchrotron radiation power per ring	[W]	1.5×10^{-4}	8.8
Initial beam and luminosity lifetimes			
Beam current lifetime (beam-beam, residual gas)	[hour]	-	< 21.8
Luminosity lifetime (as in Table 21.3)	[hour]	-	< 11.2

Only show parameters that are different from nominal scheme

Some things are straightforward …

- Beam current and stored energy 100 times lower

  Many limits to performance of proton beams are not a problem for lead ion beams

  - impedance-driven collective effects
  - beam-beam
  - electron cloud
  - activation and maintenance of collimators

- Same *geometrical* transverse beam size and emittance $\Rightarrow$ some aspects are similar

  Considerations of optics, dynamic aperture, mechanical acceptance, etc. more or less carry over from protons.

Electromagnetic Interactions of Heavy ions

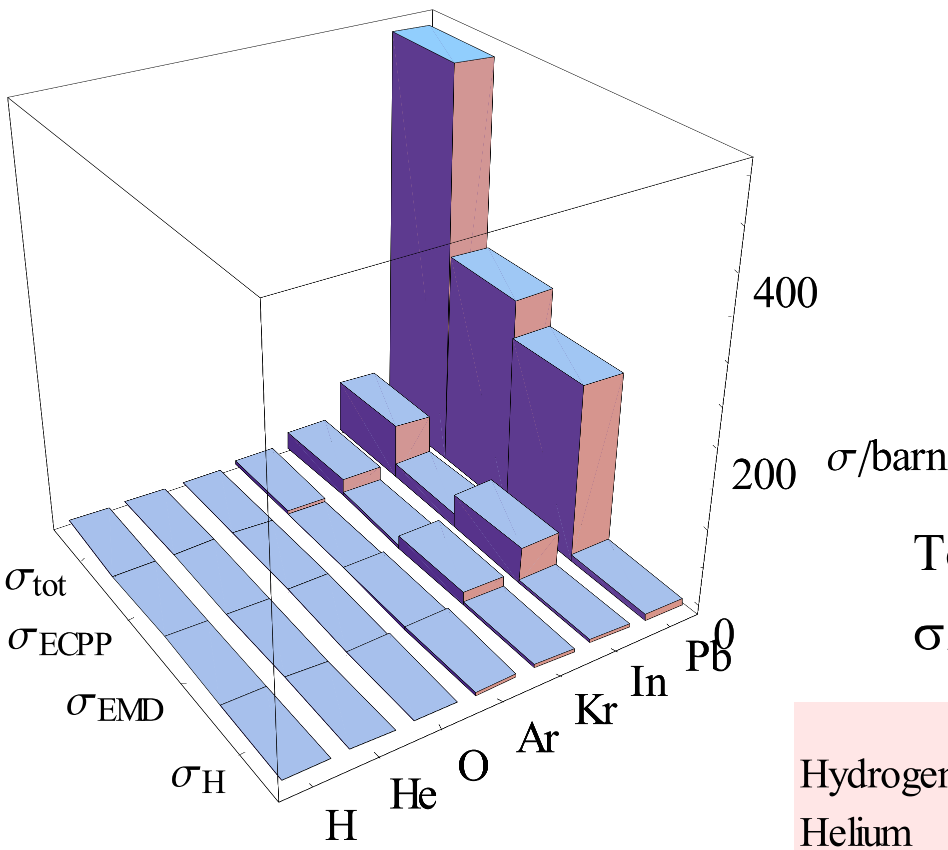
QED effects in the peripheral collisions of heavy ions		
Rutherford scattering:	${}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+}$	Copious but harmless
Free pair production:	${}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} + \mathrm{e}^+ + \mathrm{e}^-$	Copious but harmless
Electron capture by pair production (ECPP)	${}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{81+} + \mathrm{e}^+$ Electron can be captured to a number of bound states, not only 1s.	Secondary beam out of IP, effectively off-momentum" $\delta_p = \frac{1}{Z-1} = 0.012 \quad \text{for Pb}$
Electromagnetic Dissociation (EMD)	${}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + ({}^{208}\mathrm{Pb}^{82+})^* \downarrow {}^{207}\mathrm{Pb}^{82+} + \mathrm{n}$	Secondary beam out of IP, effectively off-momentum: $\delta_p = -\frac{1}{A-1} = -4.8\times10^{-3} \text{ for Pb}$

Other processes have smaller cross sections.

Importance of ECPP for machine first pointed out by Spencer Klein.

Nuclear cross sections

- Cross-section for Pb totally dominated by electromagnetic processes
- Values for non-Pb ions may need upward revision



ECPP from Meier et al, Phys. Rev. A, **63**, 032713 (2001), calculation for Pb-Pb at LHC energy

Total cross - section for ion removal from beam

$$\sigma_{tot} = \sigma_H + \sigma_{EMD} + \sigma_{ECPP}$$

	σ_H	σ_{EMD}	σ_{ECPP}	σ_{tot}
Hydrogen	0.105	0	4.25×10^{-11}	0.105
Helium	0.35	0.002	$1.\times10^{-8}$	0.352
Oxygen	1.5	0.13	0.00016	1.63016
Argon	3.1	1.7	0.04	4.84
Krypton	4.5	15.5	3.	23.
Indium	5.5	44.5	18.5	68.5
Lead	8	225.	280.756	513.756

$$\delta(\Delta Q, \Delta A) \simeq \frac{1+\Delta A/A}{1+\Delta Q/Q} - 1$$

Cross-section for ECPP

Involved topic, numerous references …

Extrapolation from SPS measurements at lower energy in Grafström et al, PAC99

Meier et al, Phys. Rev. A, **63**, 032713 (2001), calculation for Pb-Pb at LHC energy

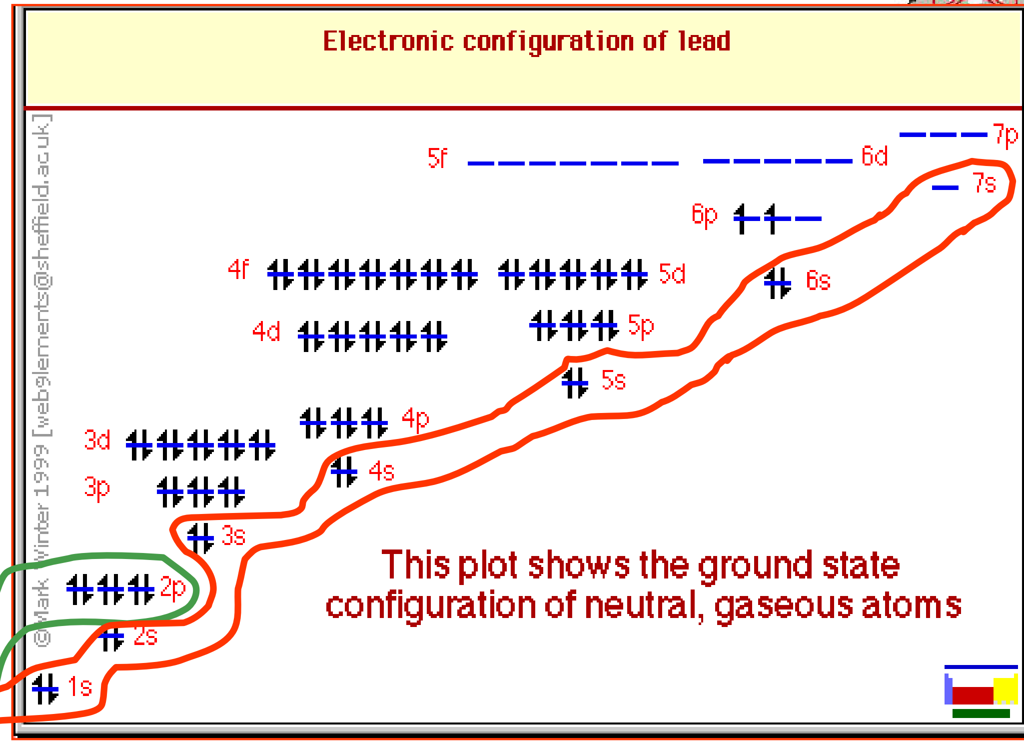
TABLE I. Cross section for the bound-free pair production of *one* ion *only* for different bound states are given for RHIC and LHC conditions for different ion-ion collisions. Also given are the parameters A and B to be used in Eq. (28) for the dependence on the Lorentz factor γ_c.

Bound state	σ(RHIC) (b)	σ(LHC) (b)	A (b)	B (b)
^{1}H-^{1}H	$\gamma_c=250$	$\gamma_c=7500$		
1s	2.62×10^{-11}	4.25×10^{-11}	5.36×10^{-12}	-3.40×10^{-12}
2s	3.28×10^{-12}	5.31×10^{-12}	6.70×10^{-13}	-4.23×10^{-13}
2p(1/2)	3.75×10^{-17}	6.10×10^{-17}	7.73×10^{-18}	-5.20×10^{-18}
2p(3/2)	1.47×10^{-17}	2.41×10^{-17}	3.10×10^{-18}	-2.42×10^{-18}
3s	9.70×10^{-13}	1.57×10^{-12}	1.98×10^{-13}	-1.26×10^{-13}
^{20}Ca-^{20}Ca	$\gamma_c=125$	$\gamma_c=3750$		
1s	1.61×10^{-2}	2.92×10^{-2}	3.84×10^{-3}	-2.48×10^{-3}
2s	2.00×10^{-3}	3.62×10^{-3}	4.78×10^{-4}	-3.07×10^{-4}
2p(1/2)	1.39×10^{-5}	2.52×1		
2p(3/2)	3.63×10^{-6}	6.70×1		
3s	5.90×10^{-4}	1.07×1		
^{47}Ag-^{47}Ag	$\gamma_c=109$	$\gamma_c=32$		
1s	3.51	6.46		
2s	4.33×10^{-1}	7.98×1		
2p(1/2)	2.81×10^{-2}	5.21×1		
2p(3/2)	3.80×10^{-3}	7.16×1		
3s	1.26×10^{-1}	2.34×1		
^{79}Au-^{79}Au	$\gamma_c=100$	$\gamma_c=30$		
1s	94.9	176	23.8	-14.7
2s	12.1	22.4	3.04	-1.87
2p(1/2)	3.62	6.77	9.27×10^{-1}	-6.56×10^{-1}
2p(3/2)	2.10×10^{-1}	4.01×10^{-1}	5.62×10^{-2}	-4.93×10^{-2}
3s	3.46	6.40	8.67×10^{-1}	-5.34×10^{-1}
^{82}Pb-^{82}Pb	$\gamma_c=99$	$\gamma_c=2957$		
1s	121	225	30.4	-18.7
2s	15.5	28.8	3.91	-2.39
2p(1/2)	5.21	9.76	1.34	-9.46×10^{-1}
2p(3/2)	2.78×10^{-1}	5.33×10^{-1}	7.50×10^{-2}	-6.61×10^{-2}
3s	4.42	8.20	1.11	-6.79×10^{-1}
^{92}U-^{92}U	$\gamma_c=97$	$\gamma_c=2900$		
1s	263	488	66.0	-39.0
2s	34.4	63.7	8.63	-5.10
2p(1/2)	16.7	31.3	4.30	-3.00
2p(3/2)	6.77×10^{-1}	1.30	1.83×10^{-1}	-1.63×10^{-1}
3s	9.67	17.9	2.43	-1.44

Electron can be captured to a number of bound states, not only 1s.

ECPP Cross-section

Use Meier et al's result for Pb-Pb at LHC energy:



$$\sigma_{\mathrm{ECPP}} = [\sigma_{\mathrm{ECPP}}(1s) + \sigma_{\mathrm{ECPP}}(2s) + \sigma_{\mathrm{ECPP}}(3s) + \cdots] + \sigma_{\mathrm{ECPP}}(2p_{1/2}) + \sigma_{\mathrm{ECPP}}(2p_{3/2}) + \cdots$$

$$\sigma_{\mathrm{ECPP}}(ns) \approx \frac{\sigma_{\mathrm{ECPP}}(1s)}{n^3}$$

$$\approx [225. + 28.8 + 8.2 + \cdots] + 9.76 + 0.533 + \cdots \quad \text{barn}$$

$$\approx [\zeta(3)\sigma_{\mathrm{ECPP}}(1s)] + 9.76 + 0.533 + \cdots \quad \text{barn}$$

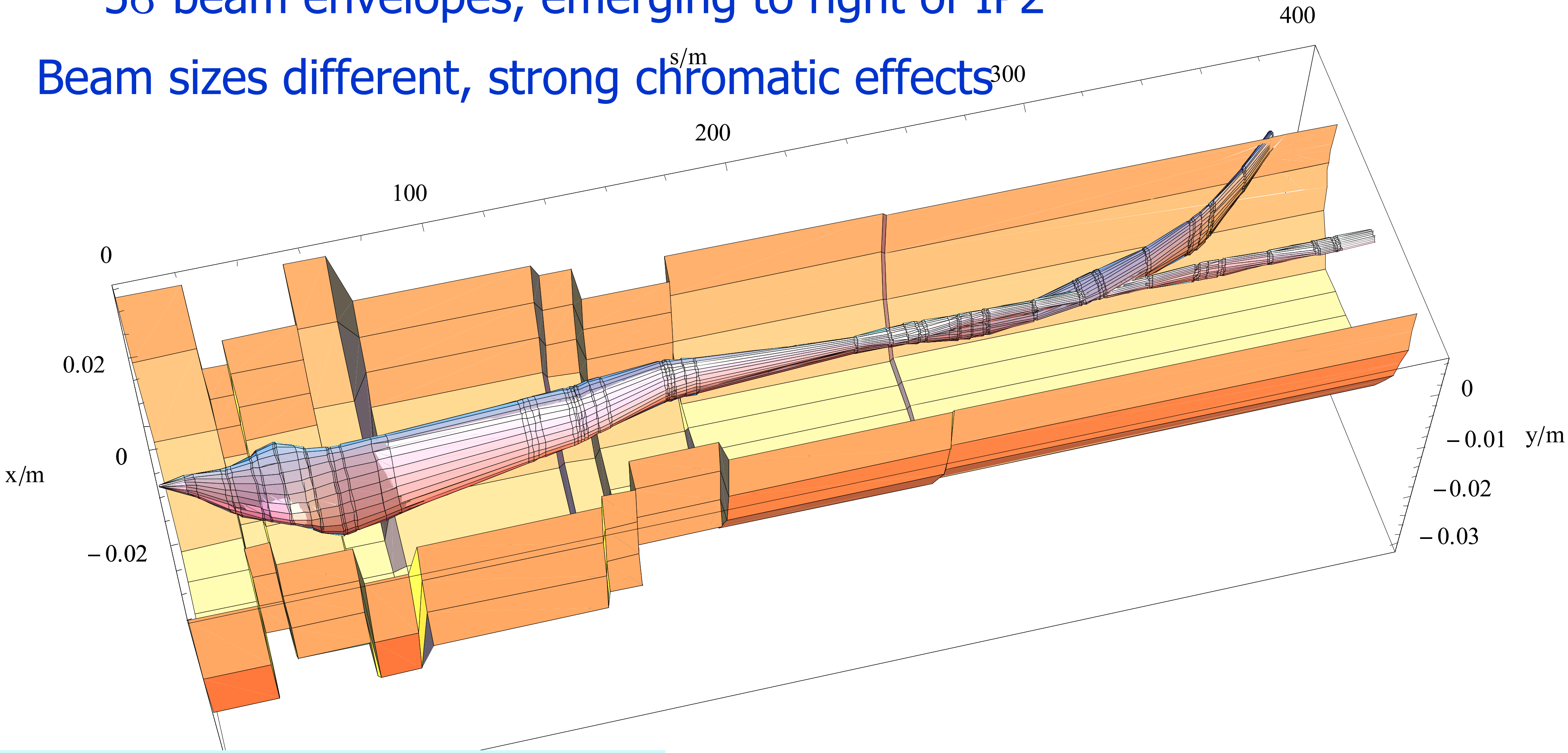
$$\approx 281\,\text{barn}$$

C.f. 204 barn used in previous discussions

Main and ECPP secondary beams

5σ beam envelopes, emerging to right of IP2

Beam sizes different, strong chromatic effects



Equivalent $\delta_p = \dfrac{1}{Z-1} = 0.012$ for Pb

Shifted momentum outside momentum acceptance $\delta_p^{\max}$

$|\delta_p| > \delta_p^{\max} \approx 6\times 10^{-3}$

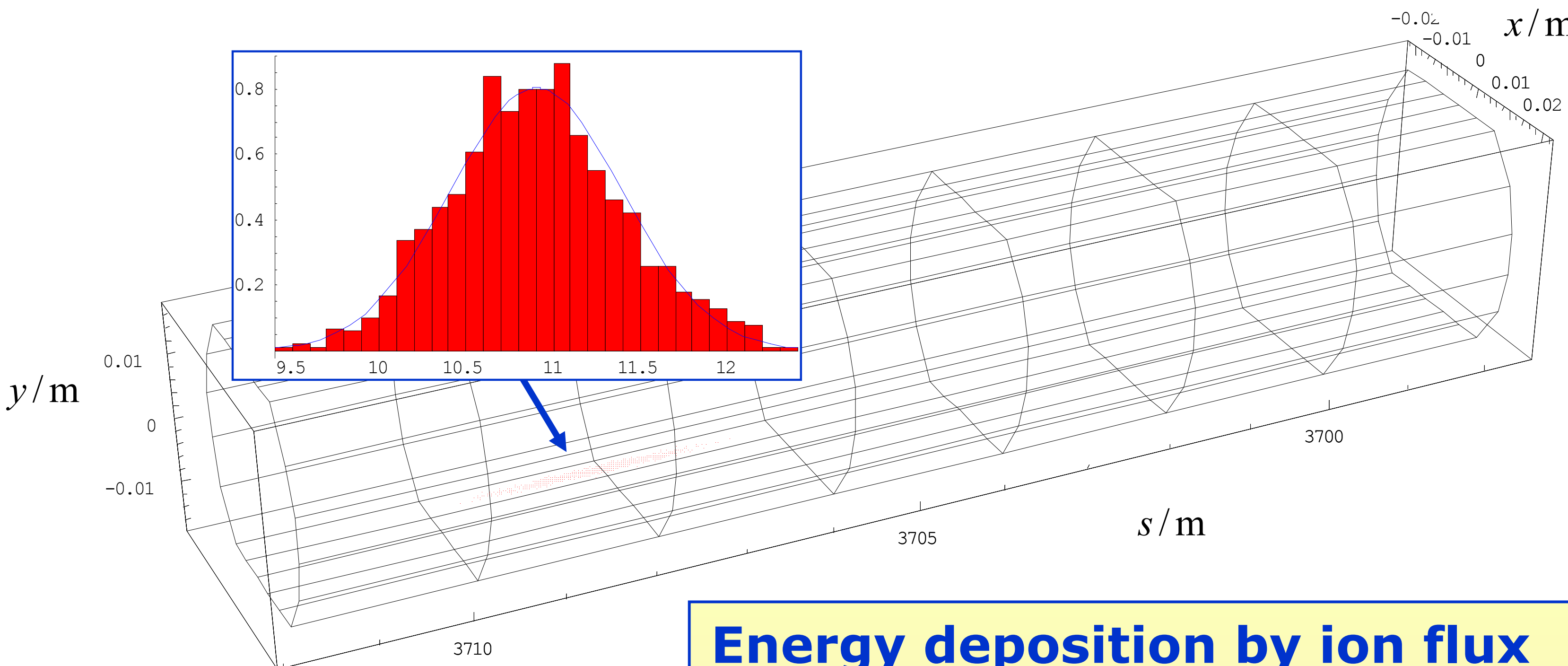
Collimation of secondary beam not easy, to be studied.

Secondary beam spot

Quench limit (conservative) is 8×10^4 Pb/m/s

Dilution over $l_d \approx 1\,\mathrm{m}$,

In quadrature with shower length $1\,\mathrm{m} \approx 1.4\,\mathrm{m}$



Beam screen in a dispersion suppressor dipole

Energy deposition by ion flux from ECPP exceeds quench limit of superconducting magnets by factor ~2 at nominal luminosity.
(some safety factors in hand ?)

Cures for ECPP?

- Collimator/spoiler

  Needs good separation of main and secondary beam, not easy

- Foil

  Re-strip ions ?

- Laser stripping?

  Huge Doppler shift helps (82 nm wavelength!)

  Power? Feasibility?

- Not seen in RHIC because of large chamber ?

  (would need D_x > 3 m for 4 cm half-width)

Consequences of EMD effect

- Magnetic rigidity of ion decreased

  Not studied in much detail so far

$$(Z_1, A_1) + (Z_2, A_2) \xrightarrow{\gamma} (Z_1, A_1) + (Z_2, A_2)^*$$

$$\downarrow$$

$$(Z_2, A_2 - 1) + \mathrm{n}$$

$$\text{Equivalent } \delta_p = -\frac{1}{A-1} = -4.8 \times 10^{-3} \text{ for Pb}$$

$$\text{Compare shifted momentum spread to momentum acceptance } \delta_p^{\max}$$

$$\left|\delta_p\right| + \sigma_\delta = 4.8 \times 10^{-3} + 0.8 \times 10^{-3} < \delta_p^{\max} \approx 6 \times 10^{-3}$$

$$\Rightarrow \text{should be taken up by momentum collimation system}$$

Collimation

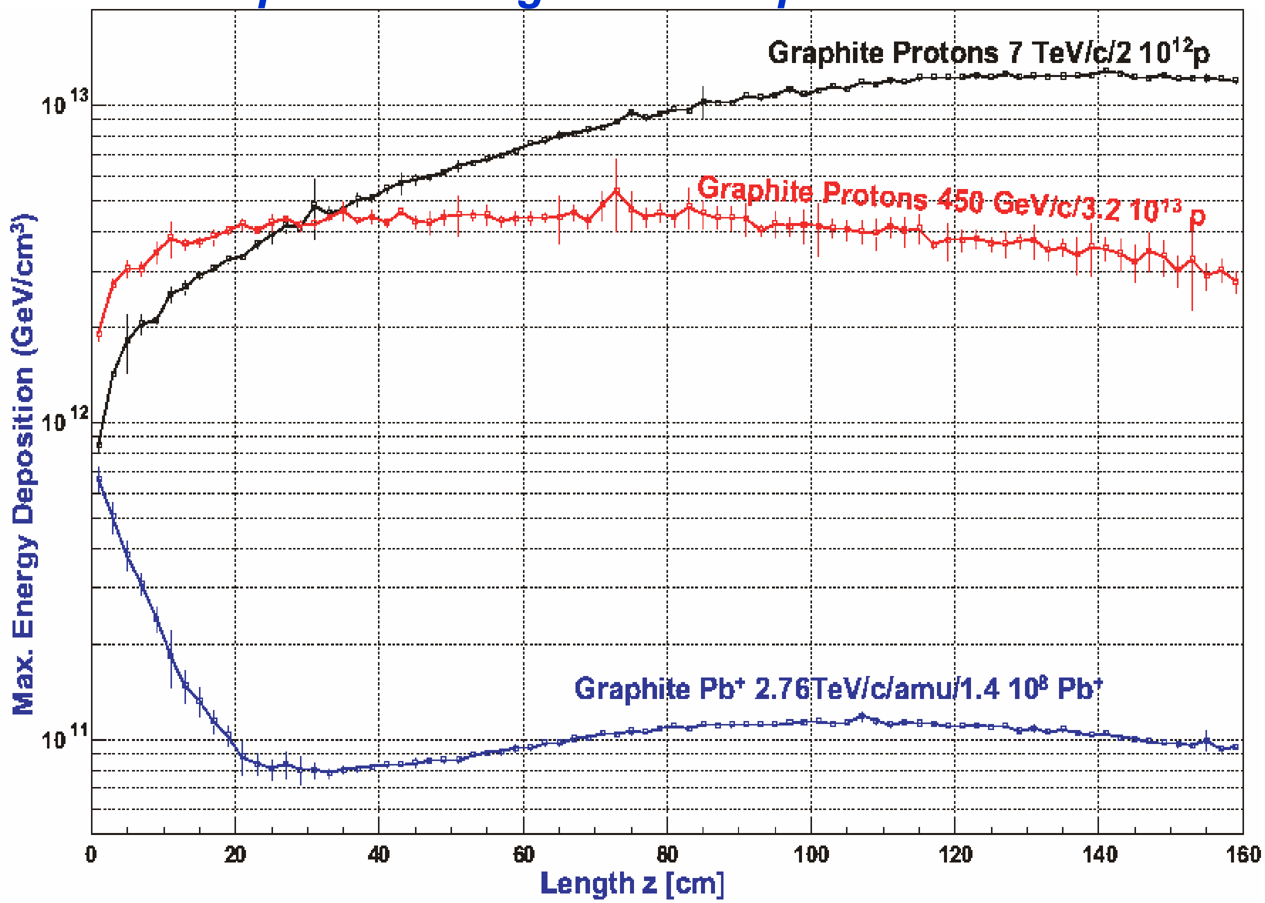
- $^{208}Pb^{82+}$ ion-graphite interactions compared with p-graphite interactions.

Physics process	p injection	p collision	$^{208}Pb^{+}$ injection	$^{208}Pb^{+}$ collision
Ionization energy loss $\frac{dE}{E\,dx}$	0.12 %/m	0.0088 %/m	9.57 %/m	0.73 %/m
Multiple scattering projected RMS angle	$73.5\,\mu\mathrm{rad/m}^{1/2}$	$4.72\,\mu\mathrm{rad/m}^{1/2}$	$73.5\,\mu\mathrm{rad/m}^{1/2}$	$4.72\,\mu\mathrm{rad/m}^{1/2}$
Electron capture length	-	-	20 cm	312 cm
Electron stripping length	-	-	0.028 cm	0.018 cm
ECPP interaction length	-	-	24.5 cm	0.63 cm
Nuclear interaction length (incl. fragmentation)	38.1 cm	38.1 cm	2.5 cm	2.2 cm
Electromagnetic dissociation length	-	-	33.0	19.0 cm

From Hans Braun

Robustness of collimator against mishaps

FLUKA calculations from Vasilis Vlachoudis
for dump kicker single module prefire

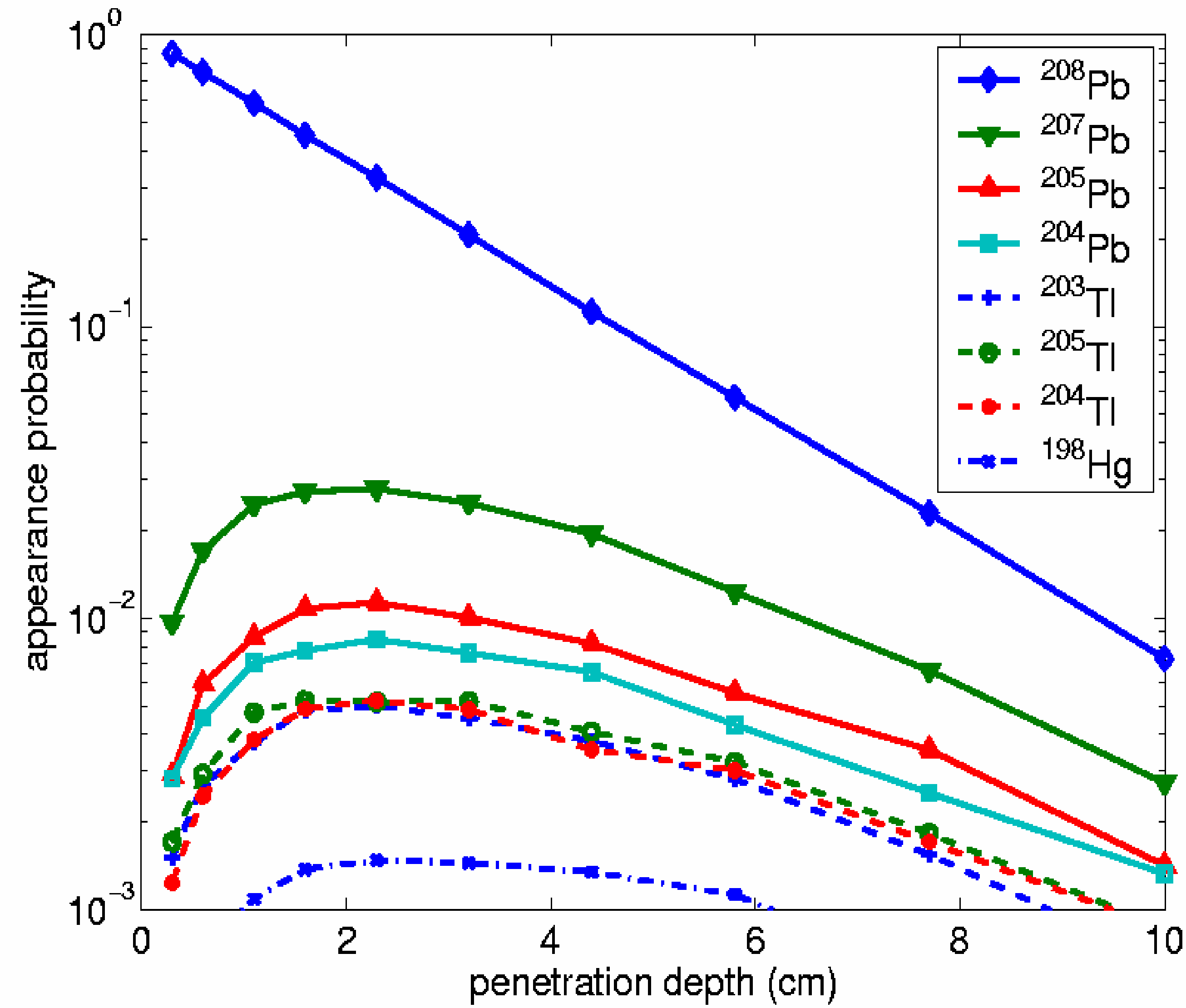


The higher Ionisation loss makes the energy deposition at the impact side almost equal to proton case, despite 100 times less beam power.

Similar damage potential.

From Hans Braun

Cleaning efficiency

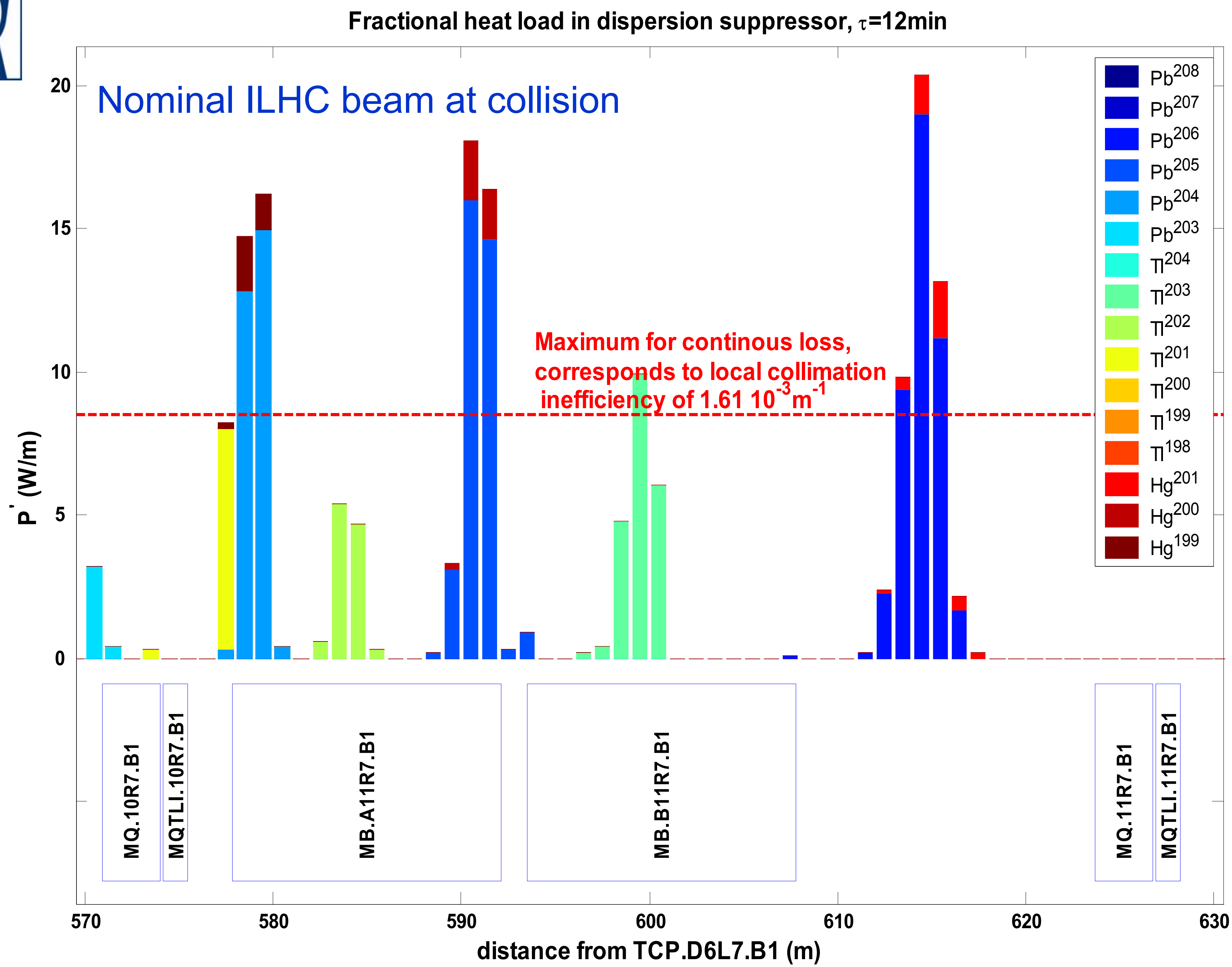


Collimators tend to put fragments on trajectories with large momentum errors and small betatron amplitude – but the secondary collimators are designed to cut betatron amplitudes

Studies under way.

The probability to convert a ^{208}Pb nucleus into a neighboring nucleus. Impact on graphite at LHC collision energy.

From Hans Braun



Fractional heat load in dispersion suppressor, τ=12min
Nominal ILHC beam at collision
Maximum for continous loss,
corresponds to local collimation
inefficiency of 1.61 10^-3 m^-1
P' (W/m)
distance from TCP.D6L7.B1 (m)
Pb208
Pb207
Pb206
Pb205
Pb204
Pb203
Tl204
Tl203
Tl202
Tl201
Tl200
Tl199
Tl198
Hg201
Hg200
Hg199
MQ.10R7.B1
MQTLI.10R7.B1
MB.A11R7.B1
MB.B11R7.B1
MQ.11R7.B1
MQTLI.11R7.B1

Optics

- Ion optics at injection/ramp
  - assumed to be essentially same as protons
- Treat only lead ion optics in collision
  - Update for move of Q3 magnets (part of V6.5)
  - Focus on IR2 (ALICE, specialised ion experiment)
    - Maintain $\beta^*=0.5$ m (unlike protons which have $\beta^*=0.55$ m for reasons of aperture)
  - Ion collisions for ATLAS/CMS may use proton optics
    - Or also squeeze further
  - Main issue is separation
    - Optics re-matched by T. Risselada

Longitudinal parameters

		Injection	Collision
Beam parameters			
Lead ion energy	[GeV]	36900	574000
Lead ion energy/nucleon	[GeV]	177.4	2759.
Relativistic "gamma" factor		190.5	2963.5
Number of ions per bunch		$7. \times 10^7$	
Number of bunches		592	
Transverse normalized emittance	$[\mu\text{m}]$	1.4[a]	1.5
Peak RF voltage (400 MHz system)	[MV]	8	16
Synchrotron frequency	[Hz]	63.7	23.0
RF bucket half-height		1.04×10^{-3}	3.56×10^{-4}
Longitudinal emittance (4σ)	[eV s/charge]	0.7	2.5[b]
RF bucket filling factor		0.472	0.316
RMS bunch length[c]	[cm]	9.97	7.94
Circulating beam current			
Stored energy per beam			
Twiss function $\beta_x = \beta_y = \beta^*$ at IP2			
RMS beam size at IP2			
Geometric luminosity reduction factor F[d]			
Peak luminosity at IP2			

Longitudinal emittance at injection from SPS has been reduced since we no longer have 200 MHz RF system for capture.

Intra-beam scattering

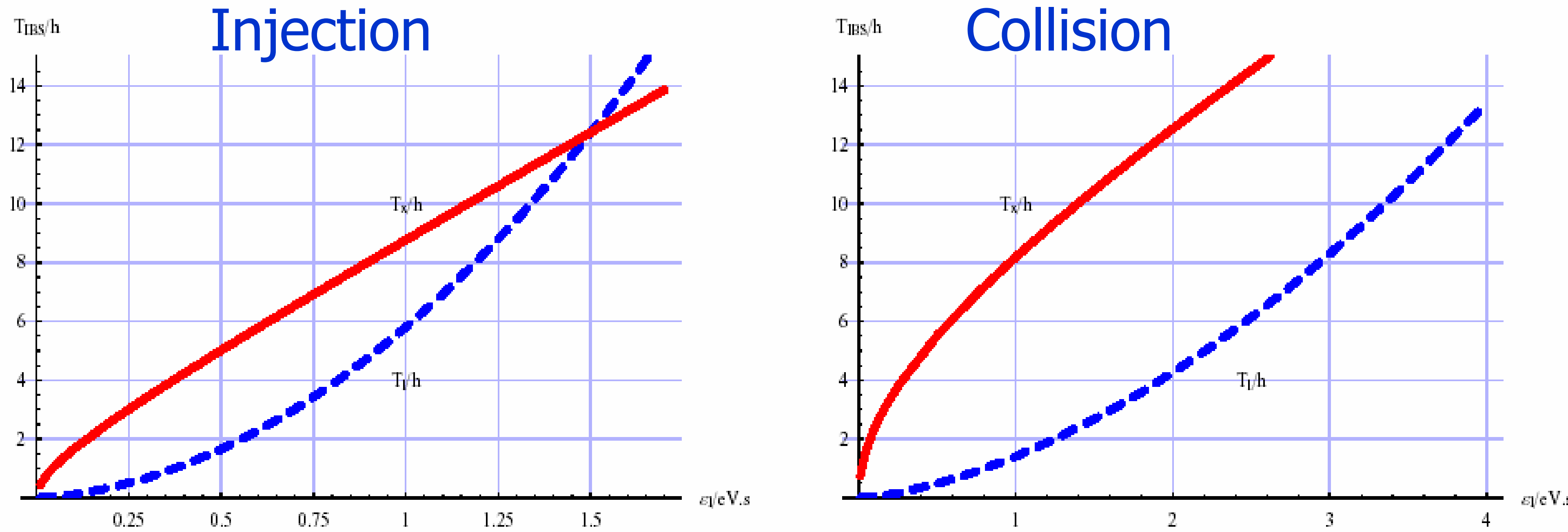


Figure 21.6: Emittance growth times from intra-beam scattering as a function of longitudinal emittance for $^{208}Pb^{82+}$ at injection (left plot) and collision (right plot) energies. The transverse emittances and beam intensities are taken to have their nominal values and the total circumferential voltage from the 400 MHz RF system are $V_{RF} = 8\,\mathrm{MV}$ and $V_{RF} = 16\,\mathrm{MV}$ respectively. Solid and dashed lines correspond to the growth times for horizontal and longitudinal emittances.

Synchrotron Radiation

- LHC is the first *proton* storage ring in which synchrotron radiation plays a noticeable role, (mainly as a heat load on the cryogenic system)
- It is also the first *heavy ion* storage ring in which synchrotron radiation has significant effects on beam dynamics.

Surprisingly, perhaps, some of these effects are stronger for lead ions than for protons.

Synchrotron radiation loss per turn

$$U = \frac{4}{3}\frac{\pi Z^2 r_p E_{\text{ion}}{}^4}{c^6 A^4 m_p{}^3 \rho}, \qquad E_{\text{ion}} = \frac{Z}{A} E_p$$

Synchrotron Radiation

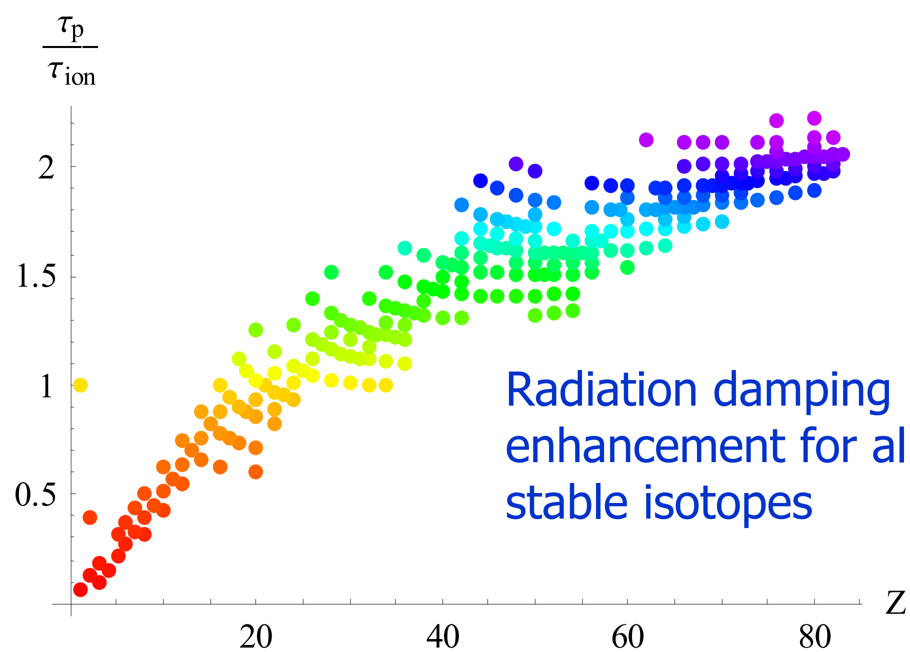
- Scaling with respect to protons *in same ring, same magnetic field*

$$\frac{U_{\text{ion}}}{U_{\text{p}}} \simeq \frac{Z^6}{A^4} \simeq 162, \qquad \frac{u^c_{\text{ion}}}{u^c_{\text{p}}} \simeq \frac{Z^3}{A^3} \simeq 0.061,$$

$$\frac{N_{\text{ion}}}{N_{\text{p}}} \simeq \frac{Z^3}{A} \simeq 2651, \qquad \frac{\tau_{\text{ion}}}{\tau_{\text{p}}} \simeq \frac{A^4}{Z^5} \simeq 0.5$$

Radiation damping for Pb is twice as fast as for protons

- Many very soft photons
- Critical energy in visible spectrum



Radiation damping enhancement for all stable isotopes

Lead is (almost) best, deuteron is worst.

Damping partition number variation

Variation of longitudinal damping partition number with momentum deviation of closed orbit:

$$\alpha_\varepsilon(\delta_s)\frac{1}{\tau_\varepsilon} \propto J_\varepsilon(\delta_s), \quad \alpha_x(\delta_s) = \frac{1}{\tau_x} \propto (3 - J_\varepsilon(\delta_s))$$

$$J_\varepsilon(\delta_s) = \frac{d \log U(\delta_s)}{d\delta_s} \approx 2 + \frac{I_4}{I_2} + 2\frac{I_8}{I_2}\delta_s, \qquad \delta_s = -\frac{1}{\eta}\frac{\Delta f_{\mathrm{RF}}}{f_{\mathrm{RF}}}$$

$$I_2 \approx \frac{2\pi}{\rho}, \quad I_4 \approx 10^{-3} I_2,$$

$$I_8 = \oint (K_1(s) D_x(s))^2 ds$$

Damping rate for horizontal betatron motion

$$\alpha_x(\delta_s) = J_x(\delta_s)\alpha_x(0) = (3 - J_\varepsilon(\delta_s))\alpha_x(0)$$

- Allows us to switch some radiation damping from longitudinal into horizontal motion

  Heavily used at LEP, PETRA, TRISTAN, …

  Overcome IBS, shrinking horizontal emittance to maximize integrated luminosity

  Price of a few mm negative closed orbit in arc QFs – needs further study

Luminosity and beam lifetime

- *Initial* beam (intensity) lifetime due to beam-beam interactions (non-exponential decay)

$$\tau_{NL} = \frac{k_b N_b}{n_{\text{exp}} L \sigma_{\text{tot}}} = \frac{22.4\ \text{hour}}{n_{\text{exp}}} \qquad \text{for nominal } L = 10^{27}\ \text{cm}^{-2}\text{s}^{-1}\text{with Pb - Pb}$$

where n_{exp} is the number of experiments illuminated

- But luminosity may be limited by experiment or quench limit

$$L = \frac{k_b N_b^{\ 2} f_0}{4\pi\sigma^{*2}} = \frac{k_b N_b^{\ 2} f_0}{4\pi\beta^* \varepsilon_n}\gamma$$

$$\Rightarrow \text{ can have same luminosity by varying } \beta^* \propto N_b^{\ 2}$$

β*-tuning during collision to maximise integrated luminosity – especially if N_b can be increased.

Luminosity and beam lifetime

- *Initial* beam (intensity) lifetime due to beam-beam interactions (non-exponential decay)

$$\tau_L = \frac{k_b N_b}{n_{\exp} L \sigma_{\mathrm{tot}}} = \frac{22.4 \text{ hour}}{n_{\exp}} \quad \text{for nominal } L = 10^{27} \text{ cm}^{-2}\text{s}^{-1} \text{with Pb - Pb}$$

where n_{exp} is the number of experiments illuminated

- But luminosity may be limited by experiment or quench limit (see later)

$$L = \frac{k_b N_b{}^2 f_0}{4\pi\sigma^{*2}} = \frac{k_b N_b{}^2 f_0}{4\pi\beta^* \varepsilon_n}\gamma$$

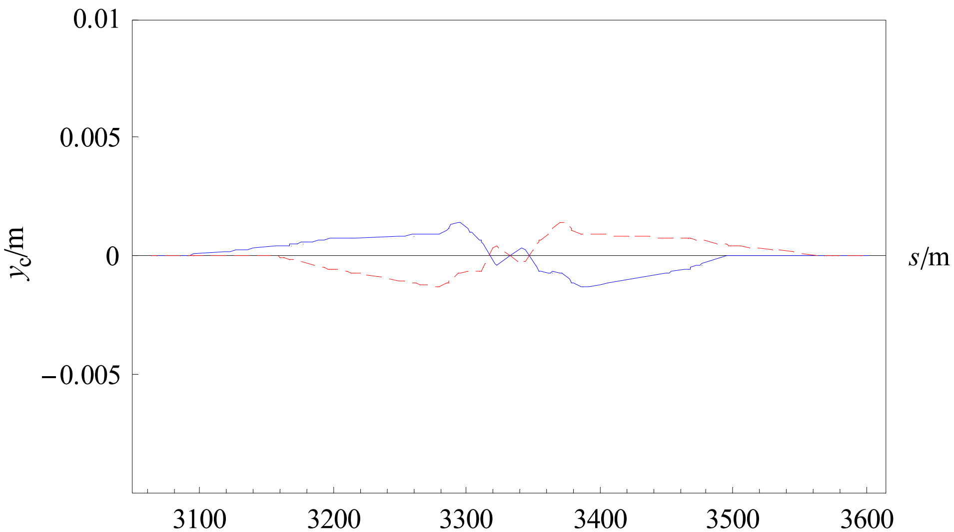
$$\Rightarrow \text{ can have same luminosity by varying } \beta^* \propto N_b{}^2$$

Idea of β*-tuning during collision to maximize integrated luminosity – especially if N_b can be increased.

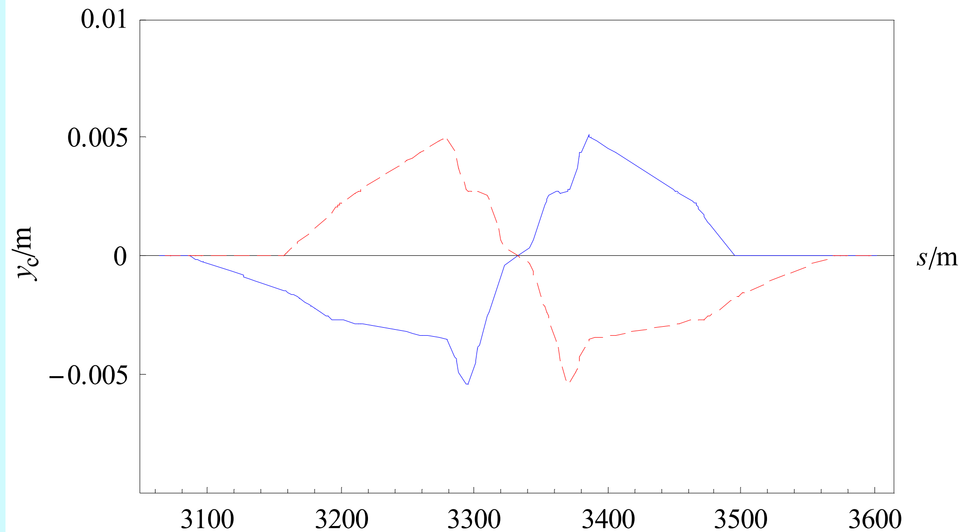
Nominal scheme, lifetime parameters (again)

		Injection	Collision
Interaction data			
Total cross section	[mb]	-	514000
Beam current lifetime (due to beam-beam)[a]	[h]	-	11.2
Intra Beam Scattering			
RMS beam size in arc	[mm]	1.19	0.3
RMS energy spread $\delta E/E_0$	[10^{-4}]	3.9	1.10
RMS bunch length	[cm]	9.97	7.94
Longitudinal emittance growth time	[hour]	3	7.7
Horizontal emittance growth time[b]	[hour]	6.5	13
Synchrotron Radiation			
Power loss per ion	[W]	3.5×10^{-14}	2.0×10^{-9}
Power loss per metre in main bends	[Wm^{-1}]	8×10^{-8}	0.005
Synchrotron radiation power per ring	[W]	1.4×10^{-3}	83.9
Energy loss per ion per turn	[eV]	19.2	1.12×10^{6}
Critical photon energy	[eV]	7.3×10^{-4}	2.77
Longitudinal emittance damping time	[hour]	23749	6.3
Transverse emittance damping time	[hour]	47498	12.6
Variation of longitudinal damping partition number[c]		230	230
Initial beam and luminosity lifetimes			
Beam current lifetime (due to residual gas scattering)[d]	[hour]	?	?
Beam current lifetime (beam-beam, residual gas)	[hour]	-	< 11.2
Luminosity lifetime[e]	[hour]	-	< 5.6

Separation in IR2: three illustrative cases



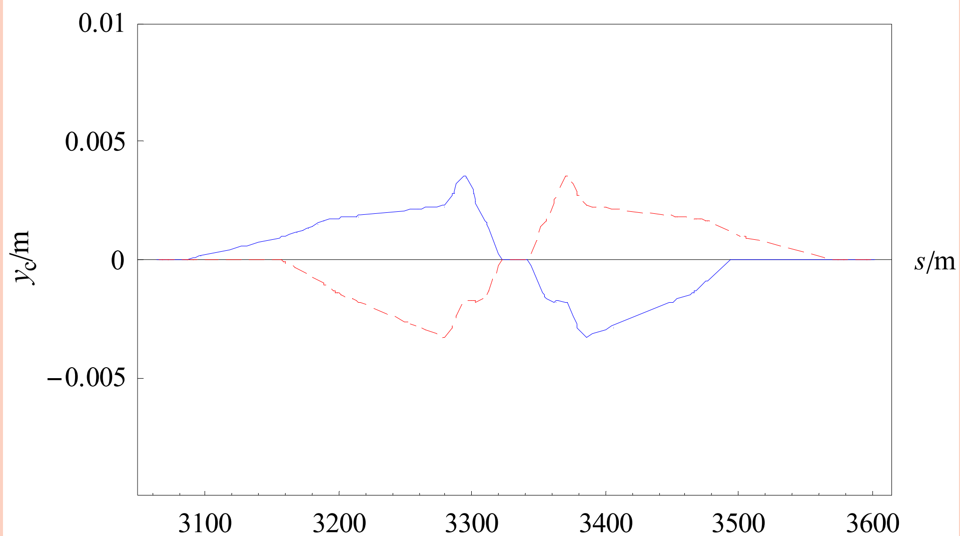
$f_{\mathrm{IP2bump}}=$ 17%, $f_{\mathrm{ALICE}}=$ 100%, $\theta_c=$ 82.2 μrad



$f_{\mathrm{IP2bump}}=$ −65%, $f_{\mathrm{ALICE}}=$ −100%, $\theta_c=$ 81. μrad

Two ways of getting a crossing angle of 80 μrad; one way to get zero crossing angle.

Beam 1 / Beam 2

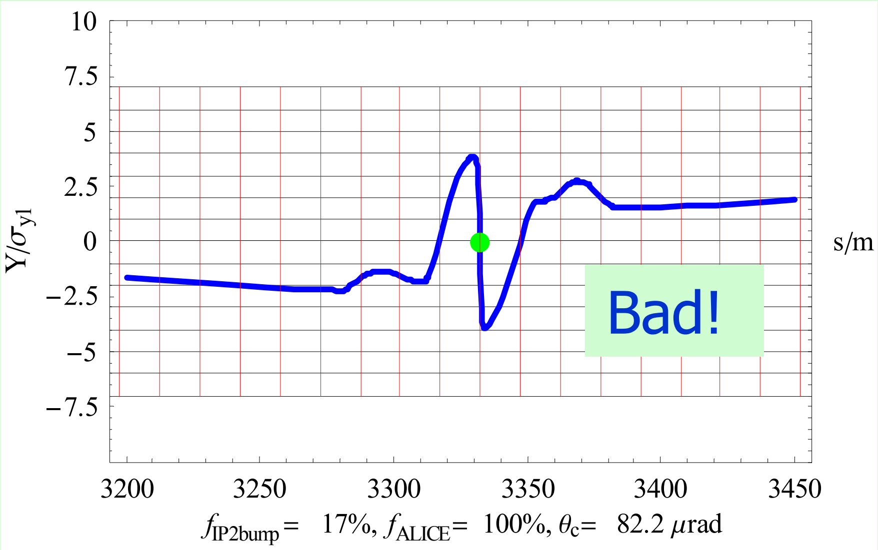


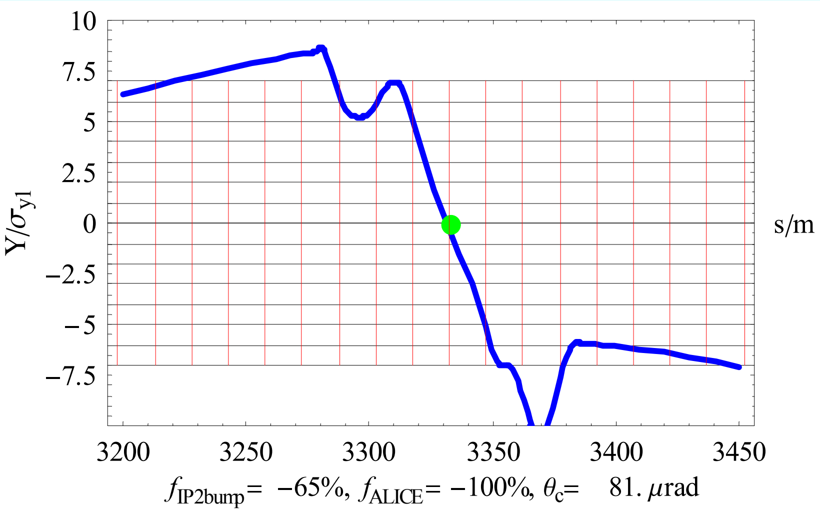
$f_{\mathrm{IP2bump}}=$ 42%, $f_{\mathrm{ALICE}}=$ 100%, $\theta_c=$ −2.8 μrad

Total separation is superposition of ALICE spectrometer bump and “external” vertical separation

Animation!

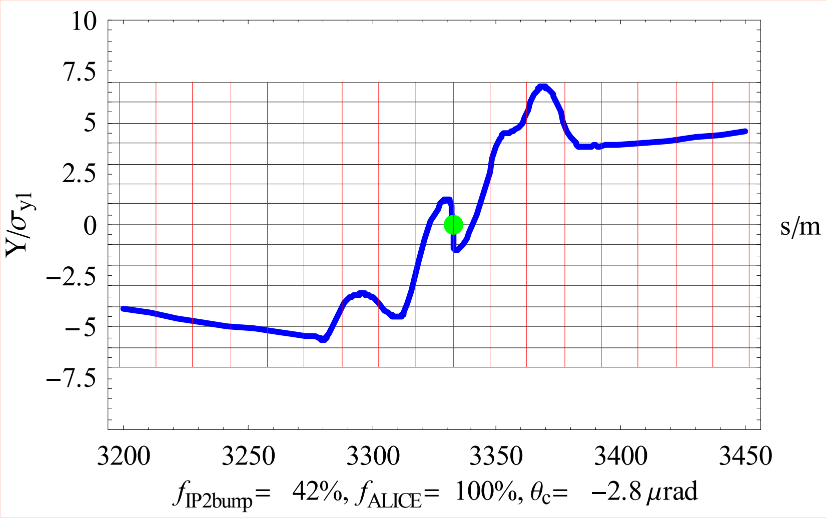
Parasitic beam-beam encounters





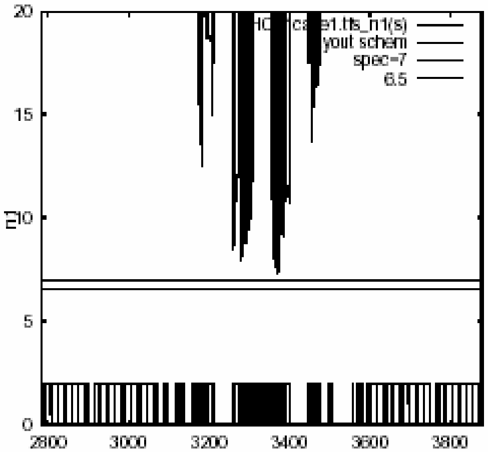
Show only vertical separation in units of vertical RMS beam size of Beam 1.

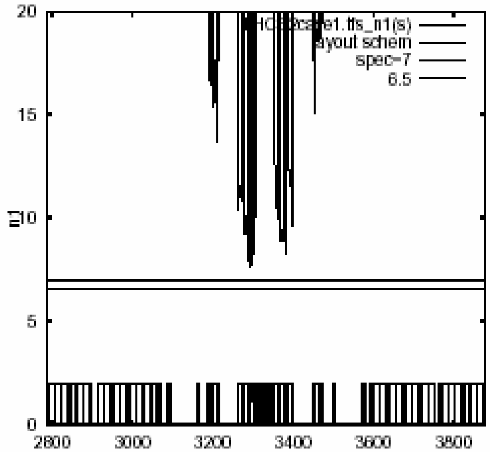
Red lines are possible (ion) encounters (S_b/2)

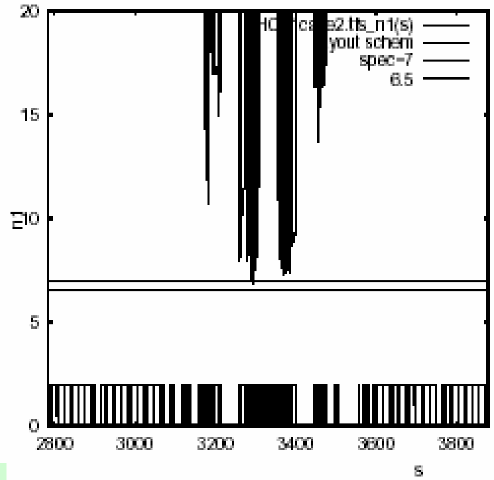


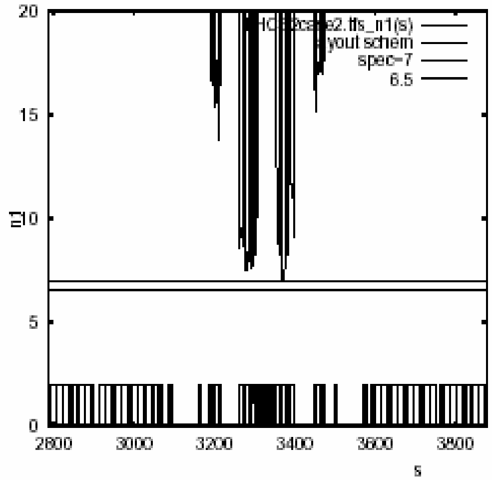
Zero crossing angle is just about achievable with minimum 3σ separation (strictly need 20 μrad).

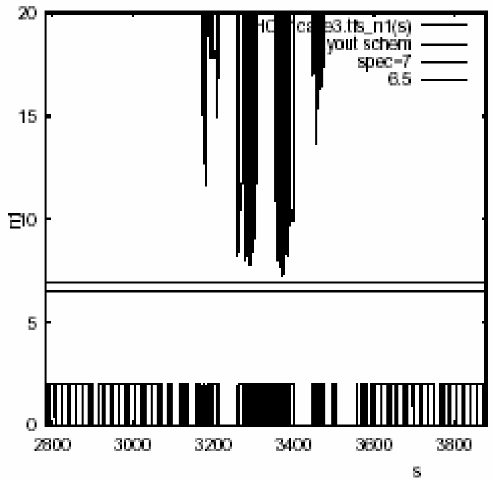
Aperture (APL program)

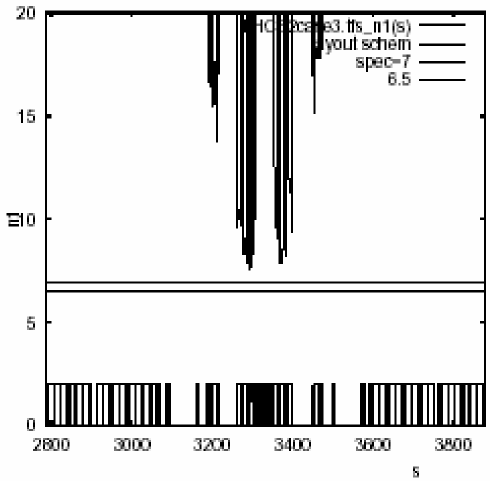












All meet the canonical aperture requirements with $\beta^*=0.5$m

Interaction of Pb ions with residual gas

- Losses due to nuclear scattering on residual gases

Atoms in residual gases (6 usual suspects in Design Report for protons) have Z≤8.

For simplicity, discuss only the dominant inelastic nuclear scattering (leave out elastic and electromagnetic contributions, EMD, ECPP which are smaller). Somewhat optimistic!

Dominant beam-gas lifetime: is independent of intensity

$$\frac{1}{\tau_{\mathrm{bg}}} = c \sum_{i \in \mathrm{gases}} \sigma_i n_i$$

Multiple Coulomb scattering on residual gas also causes emittance growth (similar to protons, not treated here).

Lost ions are a heat load:

$$P_{bg} = \frac{k_b I_b E}{Zec\,\tau_{\mathrm{bg}}}$$

Inelastic nuclear cross sections

- Cross-sections of proton-nucleus and nucleus-nucleus inelastic interactions at ~10 GeV/n, assumed similar at 2.75 TeV/n (as is the case for protons)

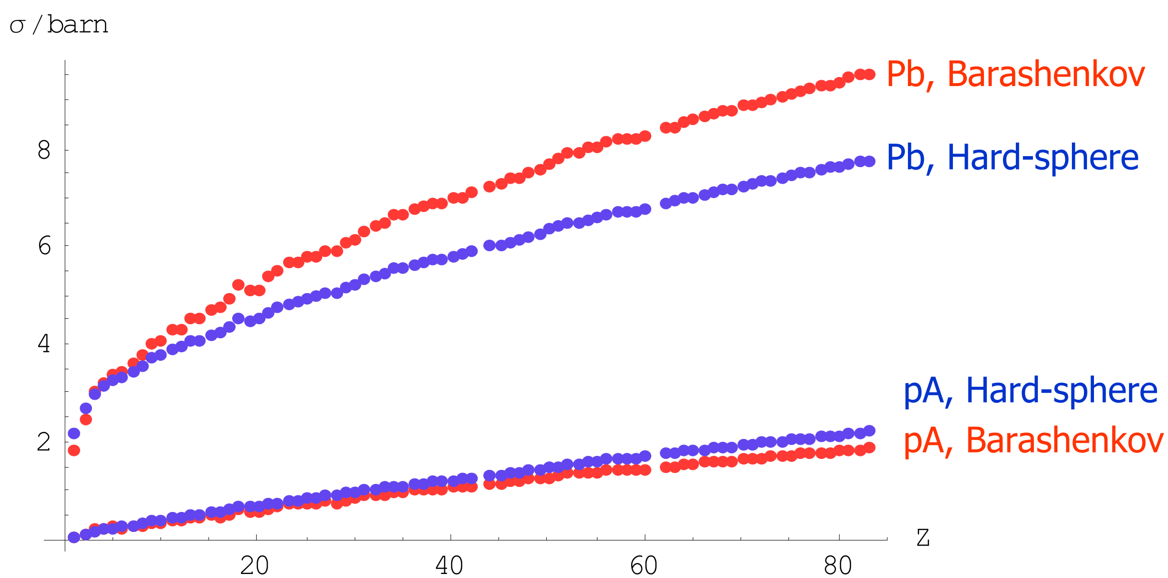
Simple formula, V.S. Barashenkov, 1993

$$\mathrm{pA}: \quad \sigma_{\mathrm{in}}(Z,A) = \sigma_0 \left[A^{1/3} + 1.85 \frac{A^{1/3}}{1+A^{1/3}} + 2.5\left(1 - \frac{2Z}{A}\right) - 1 \right]^2$$

$$\mathrm{A_1A_2}: \quad \sigma_{\mathrm{in}}(Z_1,A_1,Z_2,A_2) = \sigma_0 \left[A_1^{1/3} + A_2^{1/3} + 1.85 \frac{(A_1A_2)^{1/3}}{A_1^{1/3}+A_2^{1/3}} + 2.5\left(1 - \frac{Z_1}{A_1} - \frac{Z_2}{A_2}\right) - 2 \right]^2$$

where $\sigma_0 = 0.038$ barn.

Comparison with earlier Hard-sphere overlap model (Bradt & Peters 1950)



Required gas pressures

Protons with lifetime 100h

Gas	σ_{in}	n/m^{-3}	P(300K)/nTorr	P(5K)/Pa	P_{bg}/(W/m)
H2	0.09	1.03×10^{15}	32.	7.11×10^{-8}	0.0377
He	0.113	8.2×10^{14}	25.5	5.66×10^{-8}	0.0377
CH4	0.433	2.14×10^{14}	6.65	1.48×10^{-8}	0.0377
H2O	0.397	2.33×10^{14}	7.24	1.61×10^{-8}	0.0377
CO	0.56	1.65×10^{14}	5.14	1.14×10^{-8}	0.0377
CO2	0.86[illegible]	1.07×10^{14}	3.32	7.37×10^{-9}	0.0377

Lead ions with pressure that gave proton lifetime 100h

Gas	σ_{in}	n/m^{-3}	τ_{bg}/h	P_{bg}/(W/m)
H2	3.75	1.03×10^{15}	2.4	0.0165
He	2.48	8.2×10^{14}	4.55	0.00872
CH4	10.9	2.14×10^{14}	3.96	0.01
H2O	7.52	2.33×10^{14}	5.28	0.00752
CO	7.22	1.65×10^{14}	7.76	0.00512
CO2	11.	1.07×10^{14}	7.89	0.00503

Lead ions with lifetime 100h

Gas	σ_{in}	n/m^{-3}	P(300K)/nTorr	P(5K)/Pa	P_{bg}/(W/m)
H2	3.75	2.47×10^{13}	0.768	1.71×10^{-9}	0.000397
He	2.48	3.73×10^{13}	1.16	2.58×10^{-9}	0.000397
CH4	10.9	8.47×10^{12}	0.263	5.85×10^{-10}	0.000397
H2O	7.52	1.23×10^{13}	0.383	8.5×10^{-10}	0.000397
CO	7.22	1.28×10^{13}	0.399	8.86×10^{-10}	0.000397
CO2	11.	8.43×10^{12}	0.262	5.82×10^{-10}	0.000397

Vacuum: ion-induced molecular desorption

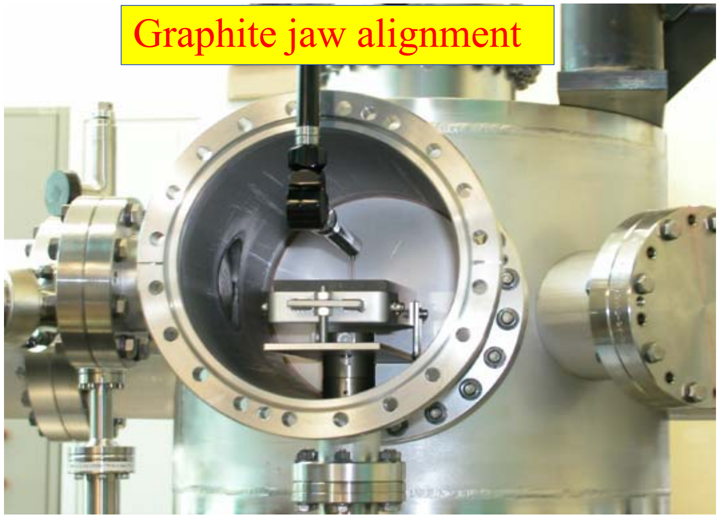
- During heavy-ion operation, alarmingly large pressure rises observed in diverse machines at CERN, GSI, BNL.
  - Dynamic pressure rise by molecular desorption from lost beam ions.
  - Not well understood, data is sparse, little information on parameter-dependences.
  - Workshop in Dec 2003 at BNL.
  - First results from recent SPS experiment are reassuring.

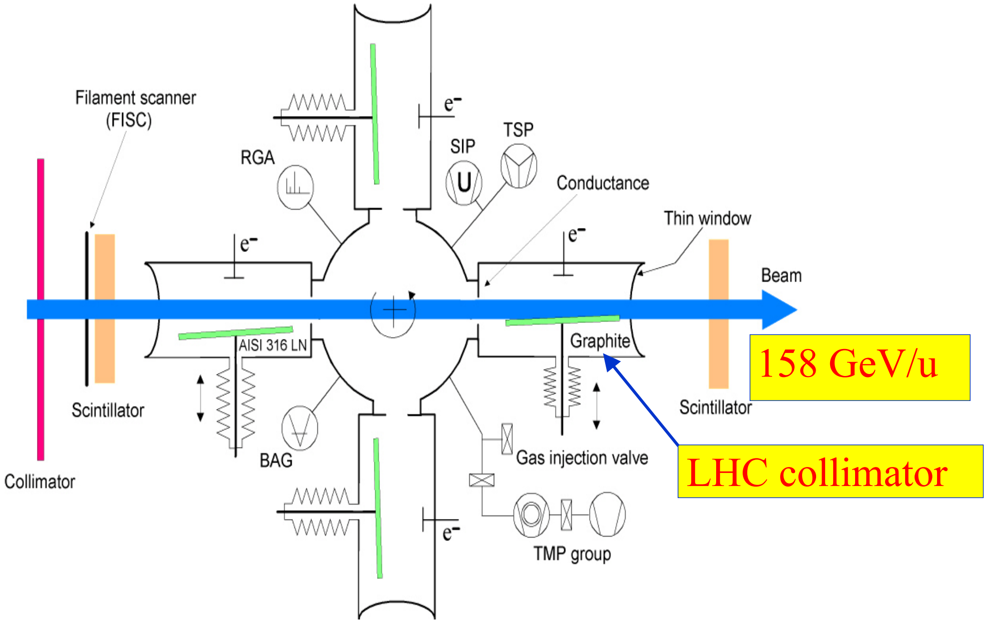
$$\eta = \frac{\Delta p\, S}{\dot{N} k_B T}$$

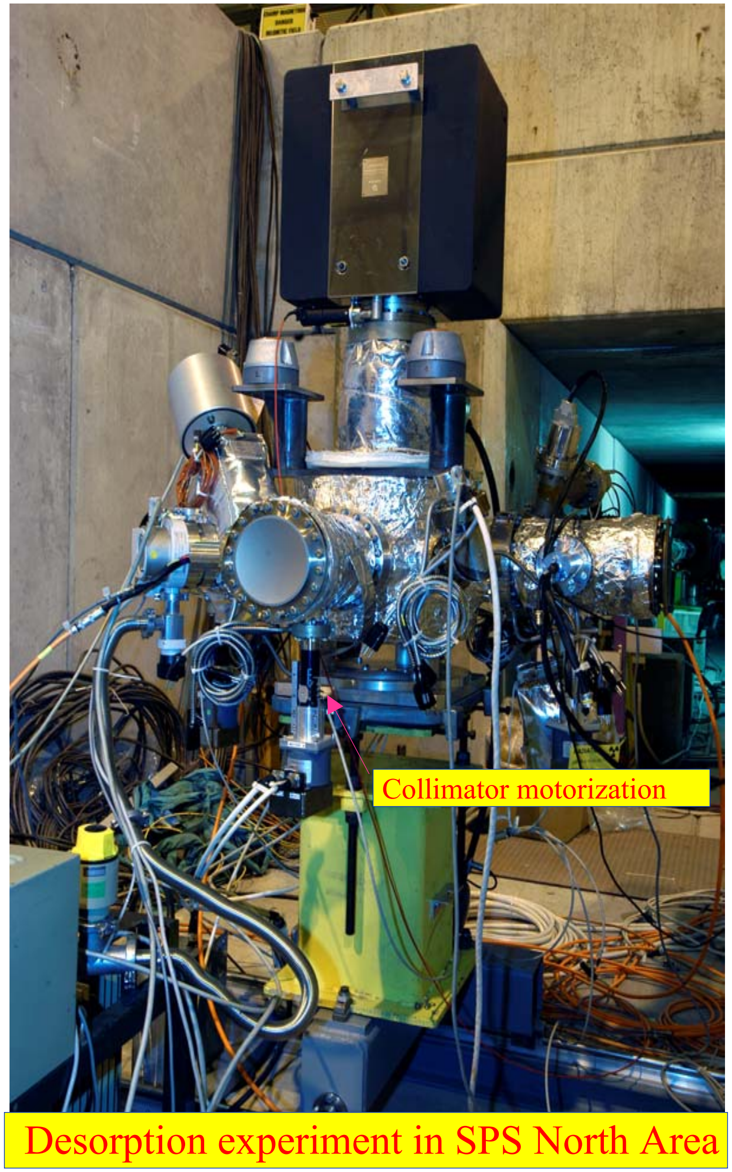
Accelerator	Energy [MeV/u]	Particle	Desorption yield [molecules/ion]
AGS	1	Au^{31+}	$\sim 10^5$
LINAC3	4.2	Pb^{53+}	$10^3 \ldots 2\times10^4$
	4.2	Pb^{27+}	$10^3 \ldots 2\times10^4$
SIS18	8.6	U^{28+}	$4\times10^3 \ldots 1\times10^4$
RHIC	8900	Au^{79+}	$\sim 1.5\times10^7$

From Edgar Mahner / AT

Dynamic outgassing tests of graphite collimators with In^{49+} at 158 GeV/u





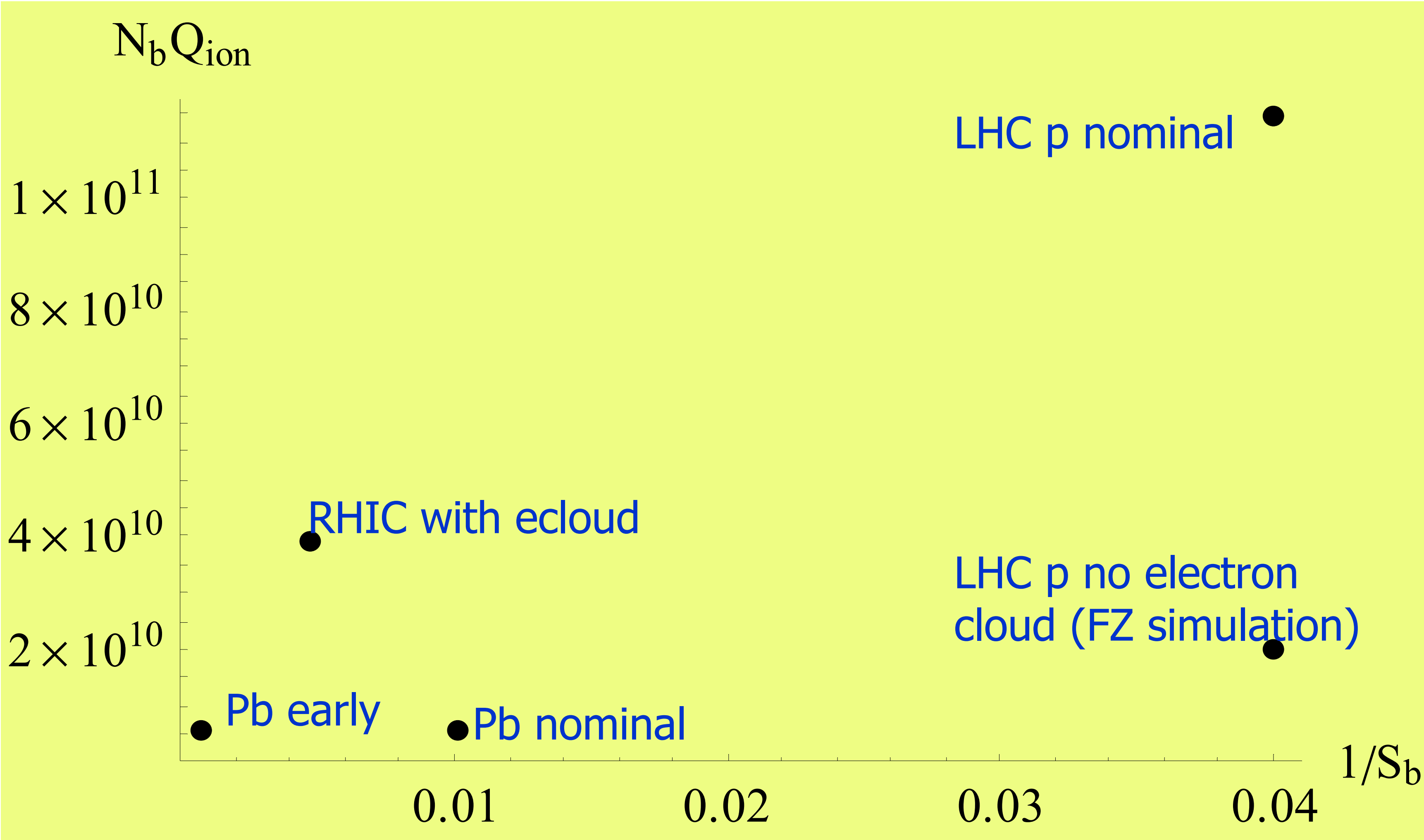


From Edgar Mahner / AT

Electron Cloud effect with ions ?

- Key parameters are charge/bunch and bunch spacing

We do not expect electron cloud effects with Pb ions.

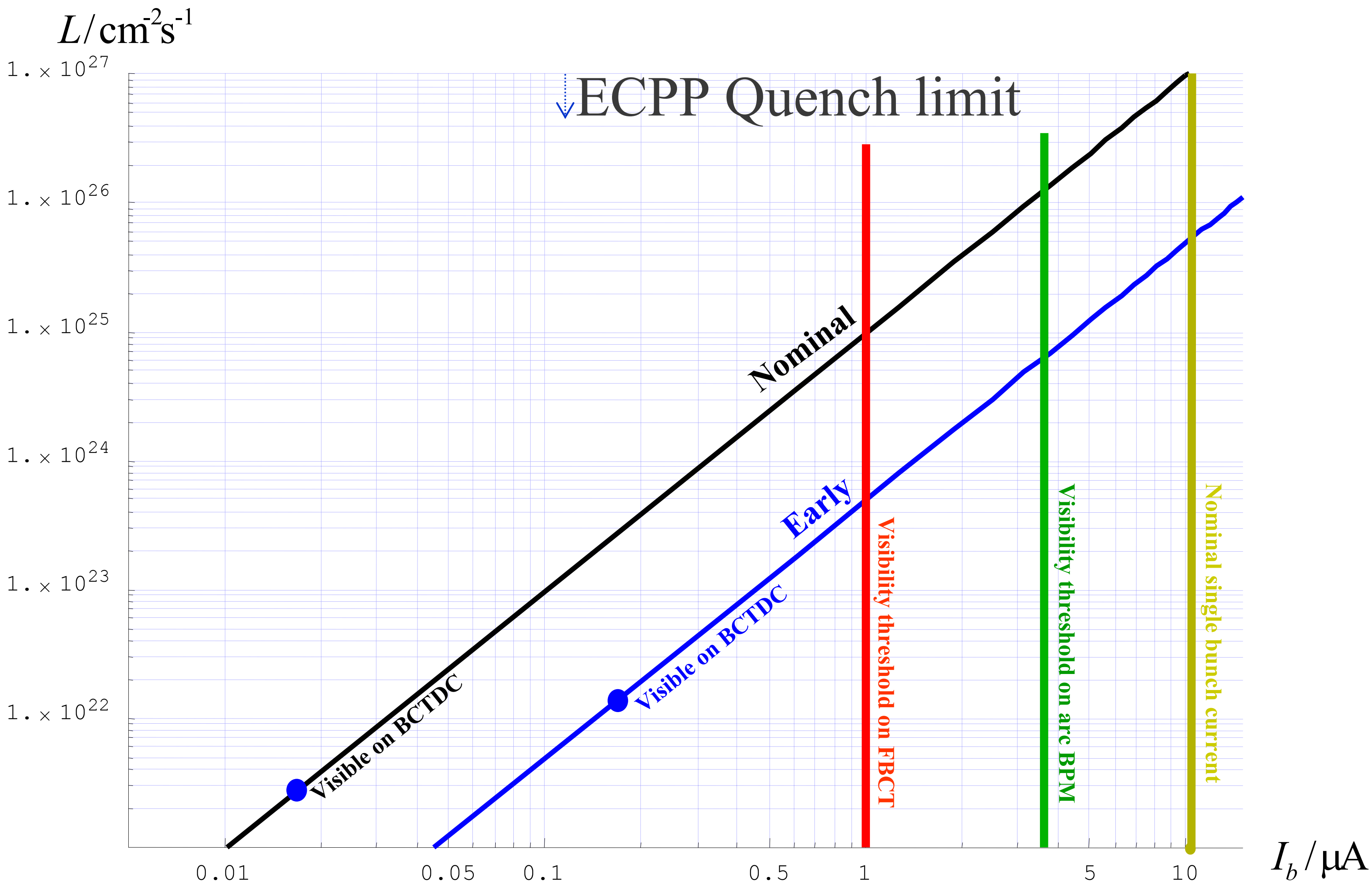


Beam Instrumentation

- Instrumentation optimised for protons early on
- Lead beams invisible on arc BPMs at about factor 3 below full intensity.

  Recent improvement of electronics
- “Early” scheme – 10 times fewer bunches but full intensity/bunch (limited by injectors)
- Visibility on beam current monitors also limited

Operational parameter space with lead ions



Thresholds for visibility on BPMs and BCTs.

Tentative I-LHC Schedule (Early Beam)

	LEIR injection line	LEIR ring	PS	SPS	LHC
Start hardware commissioning	January 2005	April 2005[1]	February 2006		
Start beam commissioning	May 2005	August 2005[1]	May 2006	(late 2006?) spring 2007	from April 2008
Problems	New source available? Hardware installed? Little time for hardware commissioning	LEIR conversion completed? Maybe running-in through winter 2005/6?	Start-up after an 18-months shutdown with new beams	SPS experts are busy commission-ing LHC ring in 2007	ALICE wants beam "at the end of 1st proton period" (Nov. 2007?)

[1] SPS and PS stopped in 2005→ "ideal" year for LEIR commissioning (more help available)

Conclusions

- LHC will open up a new regime of ultra-relativisitic heavy-ion physics
- Operation of LHC with lead ions limited by new effects, qualitatively different from protons
- Restricted to a narrow operational range of parameters below the nominal luminosity
- “Early scheme” will allow relatively safe commissioning, access good initial physics
  - Reduced risk of magnet quenches from ECPP and collimation
- Uncertainties to be resolved with further studies
  - ECPP heating, EMD losses, vacuum, collimation, RF noise, …